Matt's Code

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Contents

Chapter 1

Introduction

This document lists a bunch of the GitHub repositories created by me which may be useful to others. Some of these repositories are fairly complete, others are less so. I will do my best to fix and update anything that is buggy or incomplete, please do report bugs in the relevant repositories if you can. If you're feeling particularly helpful - feel free to send pull requests.

Most of the code here is written in Python, some things make use of C++ libraries to do some of the heavy lifting, one is a pretty dodgy Python wrapper of a C++ wrapper of Fortran code... Some of the modules and libraries used here are dependencies of others. In the more complete repos `pip` will take care of dependencies, otherwise some manual installation may be required.

1.1 Setting up the environment

In this section I describe how to set up the environment such that everything *should* pretty much work...

1.1.1 Linux

If running on ALICE/SPECTRE, you will most likely be required to enable the following modules:

```
module load gcc/9.3
module load python/gcc/3.9.10
module load git/2.35.2
```

where exact version numbers may change (use whatever is latest, don't just copy and paste!) and the replacement for SPECTRE/ALICE may have another method for loading these things in for all I know. I also recommend adding those to the end of your `/.bashrc` file so that they load every login, e.g.:

```
echo module load gcc/9.3 >> ~/.bashrc
echo module load python/gcc/3.9.10 >> ~/.bashrc
echo module load git/2.35.2 >> ~/.bashrc
```

The above is unlikely to be necessary on a local Linux installation, instead I would recommend installing `git, gcc, g++, make, gfortran` and `pip3`, e.g. in Ubuntu:

```
sudo apt install git gcc g++ binutils gfortran python3-pip
```

All of the above should allow you to install/run/compile most of my code. I wouldn't recommend using Conda in Linux - I know it has cause some problems/confusion when it comes to linking Python with C/C++ on SPECTRE.

1.1.2 Windows

A fair portion of the code is able to run on Windows - much of the Python code is platform independent and some of the C++ libraries/backends are able to be compiled using Windows. In this case, I *would* actually recommend installing Conda, as it worked for me. The GCC compilers (for C/C++/Fortran) can all be installed easily with TDM-GCC (get the 64-bit version here), just remember to put a tick in the box for "fortran" and "openmp".

1.1.3 MacOS

I managed to install the relevant packages in a virtual Hackintosh once. I don't remember how, perhaps using homebrew. Good luck...

1.2 Setting up a virtual environment

In SPECTRE I never actually bothered with a virtual environment, mistakes were made, headaches may have been avoided had I done so. This step is entirely optional, but somewhat recommended:

```
#create a virtual environment, call it what you want,
#here I call mine "env"
python3 -m venv env
```

Once this has been created, you MUST activate it before running any code, or you will just be running things globally:

```
source env/bin/activate
```

note that I am assuming that `env` exists in the current working directory, if not adjust the path accordingly! If it works, the prompt terminal prmpt should change, e.g:

```
#before:
matt@matt-MS-7B86:~$

source env/bin/activate
#after:
(env) matt@matt-MS-7B86:~$
```

1.3 Some python packages

Here are a list of Python packages which are either going to be required by most of my code, or would just be recommended:

1. ipython : best Python interpreter, forget notebooks
2. numpy : essential, don't skip
3. matplotlib : for plotting
4. scipy : loads of good stuff here
5. wheel : used to build Python packages to be installed by pip
6. cdflib : reads CDF files
7. keras : nice for machine learning
8. tensorflow : also machine learning

install them:

```
#update pip first
python3 -m install pip --upgrade --user

pip3 install ipython numpy matplotlib scipy wheel cdflib keras tensorflow --user
```

where the "`--user`" flag may or may not be necessary, depending on your version of Python - it places the installed modules in `~/.local/lib/python3.9/site-packages`.

In theory, at this point you should be able to run `ipython3` (or just `ipython`) within the terminal, from which any installed code can be imported. The reason I recommend using Ipython over the standard Python interpreter is that it has autocomplete and it uses pretty colours for syntax highlighting. It would also be a good idea to enable the autoreload feature in Ipython, which recompiles anything that has been edited since it was last run, otherwise would have to reload the code manually (or restart the session) after every edit. Run

```
ipython profile create
```

then add the following lines to ~/.ipython/profile_default/ipython_config.py:

```
c.InteractiveShellApp.extensions = ['autoreload']
c.InteractiveShellApp.exec_lines = ['%autoreload 2']
c.InteractiveShellApp.exec_lines.append('print("Warning: disable autoreload in ipython_config.py to imp
```

That should just about do it.

Chapter 2

Plasma Models

2.1 `spicedmodel`: The Scalable Plasma Ion Composition and Electron Density Model

Python wrapper for the Scalable Plasma Ion Composition and Electron Density (SPICED) model:

James, M. K., Yeoman, T.K., Jones, P., Sandhu, J. K., Goldstein, J. (2021), The Scalable Plasma Ion Composition and Electron Density (SPICED) model for Earth's inner magnetosphere, *J. Geophys. Res. Space Physics*, https://doi.org/10.1029/2021JA029565

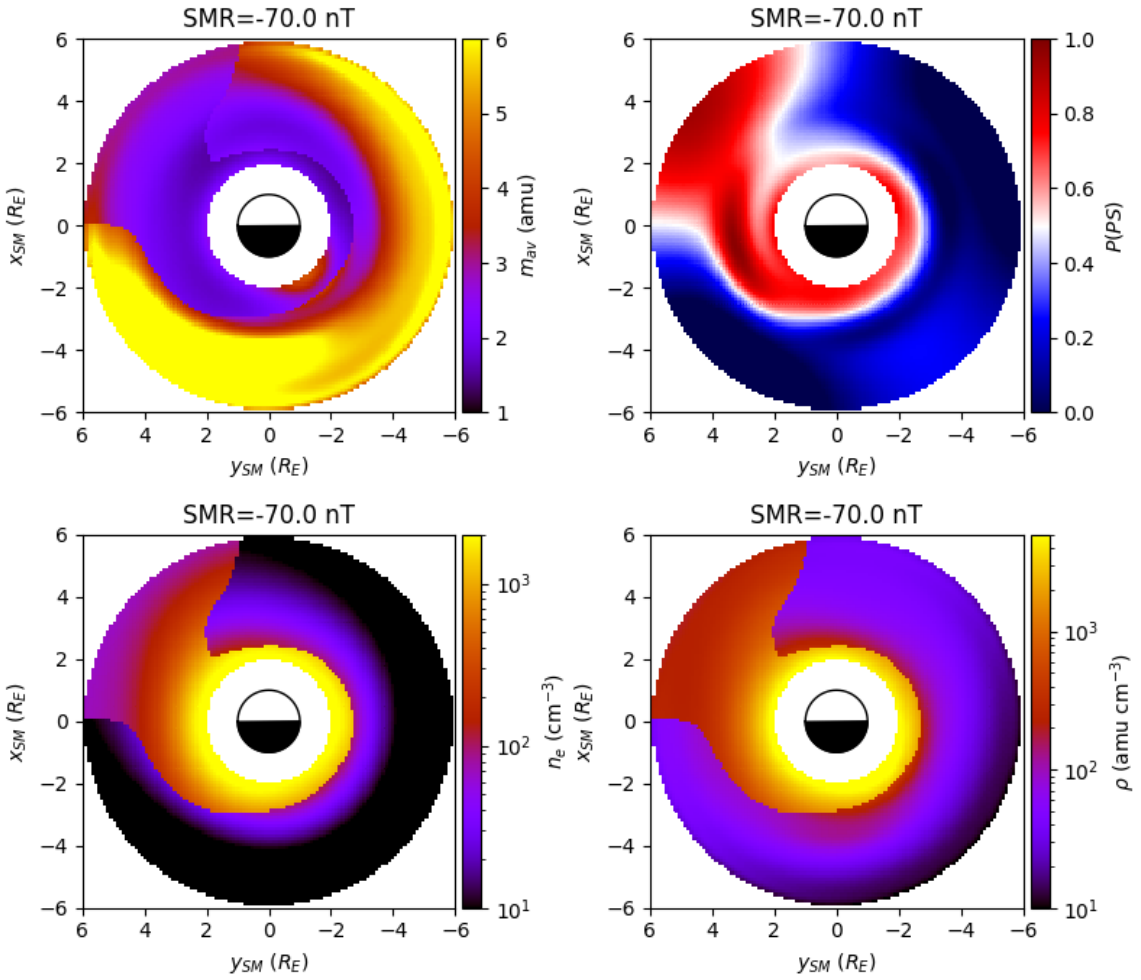


Figure 2.1: Example output of the SPICED model.

2.1.1 Installation

Using `pip`

This will download the package from PyPI:

```
pip3 install spicedmodel --user
```

From Source

Obtain the latest release from https://github.com/mattkjames7/spicedmodel

```
git clone https://github.com/mattkjames7/spicedmodel
cd spicedmodel
```

Either install using `setup.py`:

```
python3 setup.py install --user
```

or by building a wheel:

```
python3 setup.py bdist_wheel
pip3 install dist/spicedmodel-XXX.whl --user
```

where `"XXX"` is the rest of the file name, which will vary depending upon the current version.

2.1.2 Usage

Load `python3` or `ipython3`, and import

```
import spicedmodel
```

Accessing the models

There are four models, plus two additional combinations of these models:

- Plasmasphere average ion mass, $m_{av,ps}$: `spicedmodel.MavPS`
- Plasmatrough average ion mass, $m_{av,pt}$: `spicedmodel.MavPT`
- Combined average ion mass, m_{av}: `spicedmodel.Mav`
- Hot average ion mass, m_{av}: `spicedmodel.MavHot`
- Probability of being within the plasmasphere, P: `spicedmodel.Prob`
- Plasmasphere electron density, $n_{e,ps}$: `spicedmodel.PS`
- Plasmatrough electron density, $n_{e,pt}$: `spicedmodel.PT`
- Combined electron density, n_e (a combination of plasmasphere, plasmatrough and probability models): `spicedmodel.Density`
- Combined plasma mass density, ρ: `spicedmodel.PMD`

The average versions of each model can be accessed simply by providing the positions in the equatorial plane where you would like them, e.g.:

```
#either using SM x and y coordinates
P = spicedmodel.Prob(x,y)

#or using MLT (M) and L-Shell (L)
P = spicedmodel.Prob(M,L,Coord='ml')
```

The scaled models can be accessed using the same functions, this time including the `SMR` keyword (for `Mav`, `MavPS`, `MavPT`, `Prob`, `PS`, `PT`, `Density` or `PMD`) or `F107` (for `MavHot`), e.g.:

```
#electron density
ne = spicedmodel.Density(x,y,SMR=-75.0)

#average ion mass
mav = spicedmodel.Mav(x,y,SMR=-75.0)

#plasma mass density, effectively ne*mav
pmd = spicedmodel.PMD(x,y,SMR=-75.0)
```

Plotting the models

A simple function is included, `PlotEq`, which allows the plotting of any of the models in the equatorial plane, e.g.:

```
ax = spicedmodel.PlotEq(ptype,SMR=-75.0)
```

where `ptype` is used to tell the function which model to plot, available options are: `'mav'|'mavps'|'mavpt'|'mavhot'|'p`
The following code produces a plot with all 6 models when SMR = -75 nT

```
import matplotlib.pyplot as plt
import spicedmodel

#create the plot window
plt.figure(figsize=(8,7))

#set the parameters of the models
smr = -70.0

#plot the average ion mass
ax0 = spicedmodel.PlotEq('mav',SMR=smr,fig=plt,maps=[2,2,0,0])

#plot probability
ax1 = spicedmodel.PlotEq('prob',SMR=smr,fig=plt,maps=[2,2,1,0])

#plot electron density
ax4 = spicedmodel.PlotEq('density',SMR=smr,fig=plt,maps=[2,2,0,1])

#plot plasma mass density
ax5 = spicedmodel.PlotEq('pmd',SMR=smr,fig=plt,maps=[2,2,1,1])

#adjust everything to fit
plt.tight_layout()
```

2.2 spiced

GitHub: https://github.com/mattkjames7/spiced.git

The C++ code behind the SPICED model. It should be possible to build this library in Linux, Windows and MacOS.

2.2.1 Installation

In Linux and MacOS, it should eb possible to make and install the library:

```
make

#optionally install globally
sudo make install
```

Or in Windows:

```
compile.bat
```

2.2.2 Usage

When using this library, the header file should be included, i.e.:

```
#include <spiced.h>
```

and the linker flag `-lspiced` should be used during compilation.

The models also need to be initialized at runtime using `initModels();`. `spiced.h` contains a full list of the functions which can be linked to using C and other languages like Python within the `extern "C" {}` section; other symbols outside this section can, such as the model objects themselves may be interacted with directly using C++.

2.3 `HermeanFLRModel`: Model of Mercury's dayside plasma mass density

GitHub: https://github.com/mattkjames7/HermeanFLRModel.git

Estimate the dayside plasma mass density in Mercury's magnetosphere using the field line resonance (FLR) based model from James2019.

2.3.1 Installation

This hasn't been placed on PyPI, so either download fromt he GitHub page and install using `pip`, or clone and build the package:

```
#if you download the package
pip3 install HermeanFLRModel-x.y.z-py3-none-any.whl --user

#or clone, build and install
git clone https://github.com/mattkjames7/HermeanFLRModel.git
cd HermeanFLRModel
python3 setup.py bdist_wheel
pip3 install dist/HermeanFLRModel-x.y.z-py3-none-any.whl --user
```

where `x.y.z` should be replaced with the current version number.

2.3.2 Usage

Import the module and create an instance of the `Model` object:

```
import HermeanFLRModel as hflr

model = hflr.Model(Alpha,Coord='MSM')
```

where `Alpha` is the power law index which should be an integer from 0 to 6, and `Coord` sets the coordinate system to use (either MSM or MSO).

Use the `model.Calc()` member function to work out densities:

```
#create input coordinate(s)
x = np.zeros(6)
y = np.array([1.0,1.2,1.4,1.6,1.8,2.0])
z = np.zeros(6)

#call model Calc() function
rho = model.Calc(x,y,z)
```

Or produce a plot of the plasma mass denity for a slice through the magnetosphere, e.g.:

```
#select magnetic local time and alpha
MLT = 6.0
Alpha = 3.0

#plot it
ax = hflr.PlotModelSlice(MLT,Alpha)
```

which should produce something like figure 2.2.

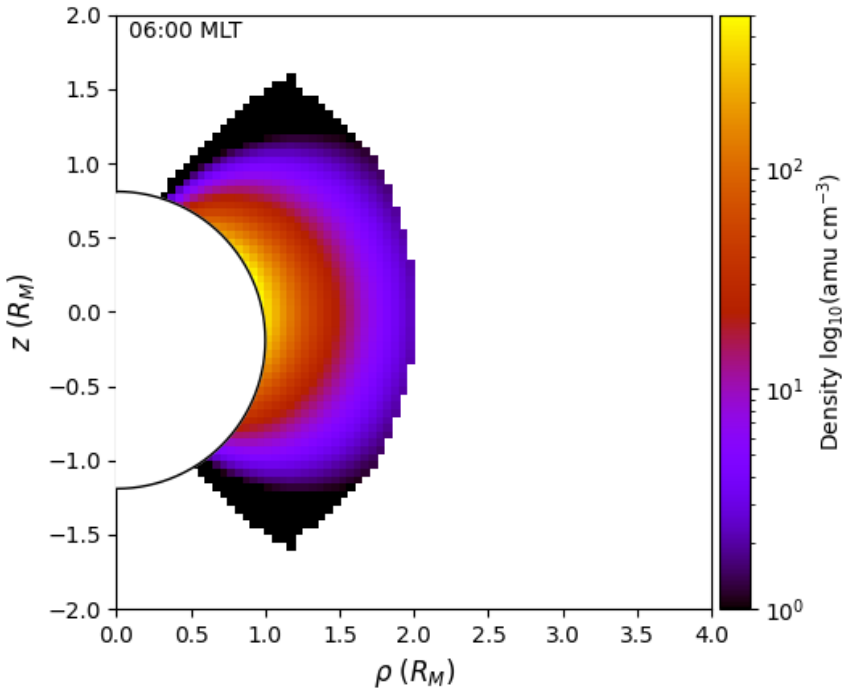


Figure 2.2: Plasma mass density at 6:00 MLT.

2.4 PyGCPM: Wrapper for the Global Core Plasma Model

GitHub: https://github.com/mattkjames7/PyGCPM.git

This is a Python wrapper for the Global Core Plasma Model (Gallagher2000, code found here)

2.4.1 Installation

This module exists on PyPI, so can be installed using `pip`:

```
pip3 install PyGCPM --user
```

2.4.2 Usage

There are three functions:

1. `PyGCPM.GCPM()`: provides particle densities at positions defined in SM coordinates.
2. `PyGCPM.PlotEqSlice()` : plots the density of a species in the equatorial plane.
3. `PyGCPM.PlotMLTSlice()` : plots the density of a particle species in

Firstly, get some densities at some positions in SM coordinates, units of R_E:

```
import PyGCPM
ne,nH,nHe,nO = PyGCPM.GCPM(x,y,z,Date,ut,Kp=Kp,Verbose=Verbose)
```

where `Date` is the date in the format yyyymmdd, `ut` is the time in hours, `Kp` is the Kp index and `Verbose=True` would display progress. The outputs of this function `ne`, `nH`, `nHe` and `nO` are the densities of electrons, protons, helium ions and oxygen ions, respectively.

We can plot the density of a particle species in the equatorial plane:

```
PyGCPM.PlotEqSlice(20010902,12.0,Parameter='ne')
```

which should produce the plot in figure 2.3.

We can also plot the density of a particle species in a slice of MLT:

```
PyGCPM.PlotMLTSlice(8.0,20010902,12.0,Parameter='ne')
```

which should produce the plot in figure 2.4.

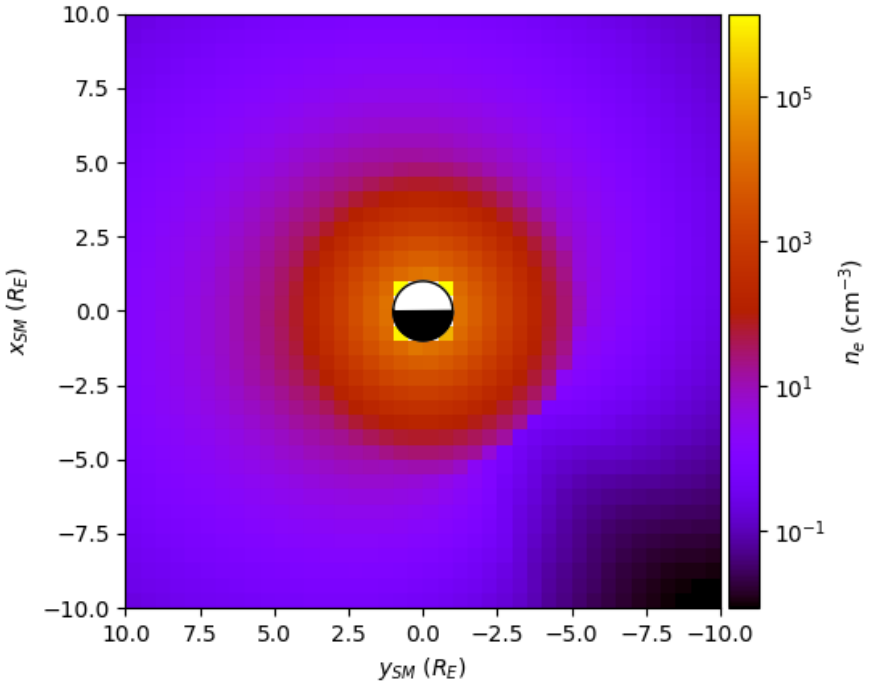


Figure 2.3: Equatorial electon density.

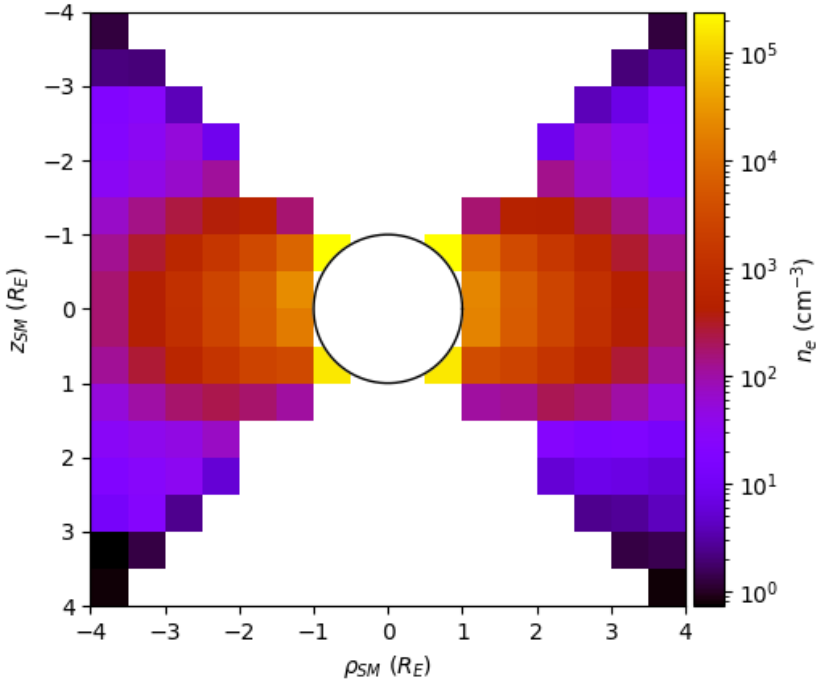


Figure 2.4: MLT slice of electon density.

Chapter 3

Field Models

3.1 PyGeopack: Python wrapper for the Tsyganenko field models

This is a Python module for obtaining field vectors and traces of the Tsygenenko field models. It is a wrapper of a wrapper (see 3.2). The latest code can be viewed and downloaded from here: https://github.com/mattkjames7/PyGeopack.

3.1.1 Installation

The easiest way to install `PyGeopack` is using `pip`, e.g.:

```
pip3 install PyGeopack --user
```

for other installation methods, see the GitHub repo.

At this point, it *may* just work if you were to try to import it, but there's a reasonably good chance that the C++/Fortran code will need to be recompiled, in which case we need to ensure that there are compilers available to do this (see section sectSetup).

One of the features of PyGeopack is that it can easily package together all of the geomagnetic/solar wind parameters that the models use so that when you request a trace or a field vector for a specific date and time, it will automatically try to find the appropriate parameters. This isn't strictly necessary for the models to work, as they will default to some fairly average parameters and they can be overridden manually. In order to be able to use this functionality, this module and the submodules which it relies on to collect the relevant data need to know where they can store the parameters. This means exporting a few environment variables (e.g. in ~/.bashrc):

```
export KPDATA_PATH=/path/to/kp
export OMNIDATA_PATH=/path/to/omni
export GEOPACK_PATH=/path/to/geopack/data
```

which are set as follows for me on SPECTRE:

```
export KPDATA_PATH="/data/sol-ionosphere/mkj13/Kp"
export OMNIDATA_PATH="/data/sol-ionosphere/mkj13/OMNI"
export GEOPACK_PATH="/data/sol-ionosphere/mkj13/Geopack"
```

Once that is done, it should work...

3.1.2 Usage

The first time this is imported, there is a good chance that it will attempt to recompile itself. There will be a lot of messages on the screen, but it should finish successfully. If it fails, double check that you have the required compilers installed, raise an issue on the GitHub page if the problem persists.

If you would lke the latest model parameters, run the following:

```
import PyGeopack as gp
gp.Params.UpdateParameters(SkipWParameters=True)
```

This may take a little time, depending on how much data it needs to download. It will take all of the data and compile it into one binary file ~350 MiB in size, once this is done, it should be relatively quick loading the data into memory.

The model field vectors can be returned using the `ModelField` function:

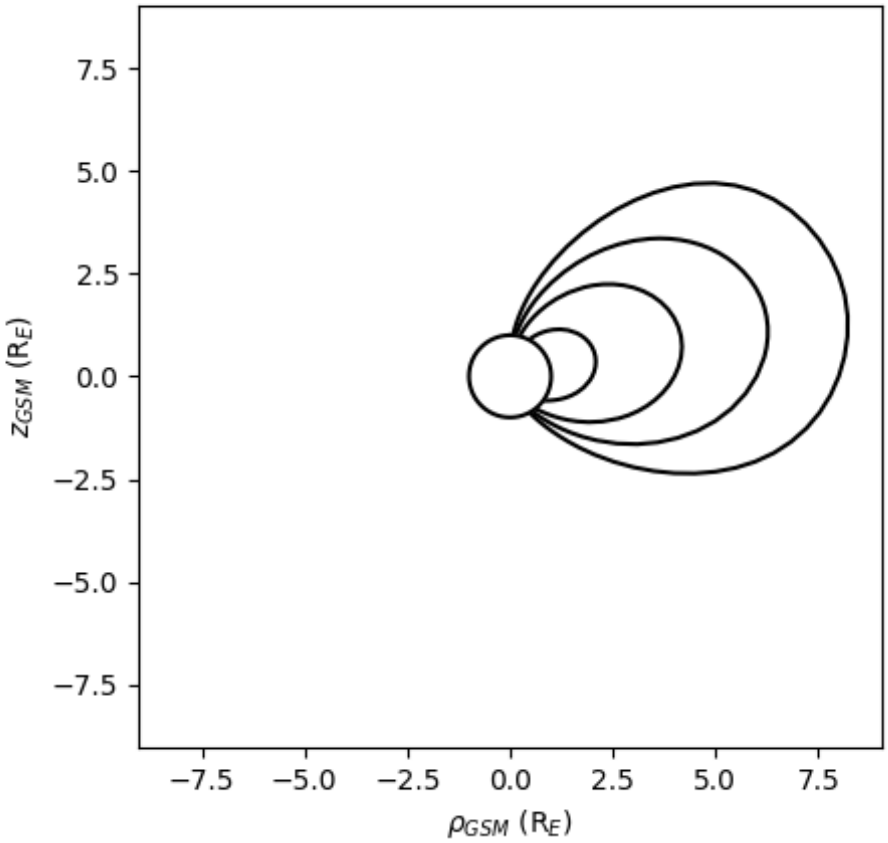


Figure 3.1: Example of field tracing using `PyGeopack`.

```
Bx,By,Bz = gp.ModelField(x,y,z,Date,ut,Model='T96',CoordIn='GSM',**kwargs)
```

where `x`, `y` and `z` can be scalars or arrays of position, in units of Earth radii and in the coordinate system defined by the `CoordIn` keyword (`'GSE'|'GSM'|'SM'`). `Date` can be an array or scalar of date(s) in the format yyyymmdd, while `ut` is in hours from the start of the day. The models currently available are `'T89'`, `'T96'`, `'T01'` and `'TS05'`.

Traces are simple to produce and can be done a single trace at a time, or in batches, e.g.:

```
import numpy as np

#define a few starting positions for the traces
x = np.array([2.0,4.0,6.0,8.0])
y = np.array([0.0,0.0,0.0,0.0])
z = np.array([0.0,0.0,0.0,0.0])

#run the traces, return TraceField object
T = gp.TraceField(x,y,z,20221222,16.0)

#plot field traces
ax = T.PlotRhoZ()
```

which should produce a plot similar to figure 3.1.

For more information on the keyword arguments please see the readme.

3.2 geopack: C++ wrapper for Tsyganenko field models

This is the code that `PyGeopack` calls, it provides a simple C-compatible interface for calculating field vectors, tracing and coordinate conversion. The C++ code in this library is used for configuring model parameters,

determining footprints and providing a simple interface for the models, while the Fortran code currently provides field vectors, coordinate transforms and tracing.

3.2.1 Installation

This code can be installed as a linkable library (at least on POSIX systems):

```
#clone the repo
git clone https://github.com/mattkjames7/geopack --recurse-submodules

#cd into it
cd geopack

#fetch the submodules if you forgot the
#--recurse-submodules flag on the clone command
git submodule update --init --recursive

#compile it
make
sudo make install
```

On Linux and MacOS the `sudo make install` command will place the header file at `/usr/local/include/geopack.h` and the shared object file at `/usr/local/lib/libgeopack.so`, unless the `PREFIX` keyword is set (by default `PREFIX=/usr/local`). If the `PREFIX` uses a custom path, then be sure to let the linker know where it exists, either by setting `LD_LIBRARY_PATH` or by using `-L` and `-I`.

On Windows, run `compile.bat` to create `lib libgeopack.dll`.

3.2.2 Usage

To use this code with C and C++, the header file must be included, i.e.:

```
#include <geopack.h>
```

and when compiling, the `-lgeopack` flag should be used to link to the library.

C and other languages such as Python should use the wrapper functions defined within the `extern "C" {}` section of `geopack.h`. This includes `ModelField()` for calculating model field vectors, `TraceField()` for field traces and a number of functions for coordinate conversion, e.g. `SMtoGSMUT()`. An example of how to trace a field line is in `geopack.c`.

C++ is able to use all of the functions declared in `geopack.h`, including the wrapper functions used by C. This means that direct usage of the `Trace` class is possible, an example of this is shown in `geopack.cc`.

3.3 KT17

KT17/KT14 magnetic field model for Mercury written in C++ with a Python wrapper. See Korth et al., 2015 (JGR) and Korth et al., 2017 (GRL) for more details on the models themselves.

3.3.1 Installation

Best to install using `pip3`:

```
pip3 install KT17 --user
```

The installation will require the following packages:

- numpy
- scipy
- matplotlib

Alternatively, clone this repo and build a wheel:

```
git clone https://github.com/mattkjames7/KT17.git
cd KT17
python3 setup.py bdist_wheel
pip3 install dist/KT17-1.0.0-py3-none-any.whl
```

NOTE: This module includes C++ code which does all of the model calculating and tracing. The package includes `libkt.so` for Linux and `libkt.dll` for Windows 10 - if either of these files can't be loaded, the code will attempt to recompile. If the compilation fails, then make sure that you have `g++` (version ¿= 5) and `make` installed on your system. For Windows users, install TDM-GCC.

3.3.2 Usage

Model parameters

Both `KT17.ModelField()` and `KT17.TraceField()` functions accept five different keyword arguments (`kwargs`) which affect the model:

Parameter	Model	Description
`Rsm`	KT14	Magnetopause standoff distance (R_M).
`t1`	KT14	Disk current field magnitude.
`t2`	KT14	Quasi-Harris sheet field magnitude.
`Rsun`	KT17	Distance of Mercury from the Sun (AU).
`DistIndex`	KT17	Anderson et al., 2013 disturbance index, in the range 0-97. height

If the KT17 parameters are provided, they are used to calculate the appropriate KT14 set of parameters as defined in Korth et al., 2017.

Obtaining model field vectors

To get model field vectors for some position(s) in the magnetosphere:

```
import KT17

#default model
Bx,By,Bz = KT17.ModelField(x,y,z)

#Custom KT14 model
Bx,By,Bz = KT17.ModelField(x,y,z,Rsm=1.3,t1=7.0,t2=2.5)

#Custom KT17 model
Bx,By,Bz = KT17.ModelField(x,y,z,Rsun=0.4,DistIndex=25.0)
```

where `x`, `y`, and `z` are either scalars or arrays of position(s) in the MSM coordinate system. The returned `Bx`, `By`, and `Bz` contain the magnetic field vector(s) at each position in nT. For positions which are outside of the magnetopause, the magnetic field components are returned as `NAN`.

Tracing the magnetic field

To trace the magnetic field, use the `TraceField` object:

```
T = KT17.TraceField(x0,y0,z0,**kwargs)
```

where `x0`, `y0`, and `z0` are the starting position(s) of the traces in MSM coordinates. The parameters of the trace can be provided using `**kwargs` - see the `KT17.TraceField` docstring for more information using `help(KT17.TraceField)` or `KT17.TraceField` in ipython.

`TraceField` can be saved to a file and reloaded, e.g.:

```
#save the Trace object
T.Save('Trace.bin')

#load the file
T = KT17.TraceField('Trace.bin')
```

Other routines

For a quick plot of the magnetic field in the X-Z plane run:

```
KT17.TestTrace()
```

To find out if a position in MSM coordinates is actually within the magnetopause or not, run the following:

```
KT17.WithinMP(x,y,z,Rsm=1.42)
```

To get the latitude and local times of the northern and southern open-closed field line boundaries, run:

```
ocb = KT17.ReadOCB()
```

where `ocb` is a `numpy.recarray` object which contains the following fields:

Fields
Mlt
LctN
LctS
Mlat
LatN
LatS

3.4 libinternalfield: C++ spherical harmonic model code

This library provides field vectors for spherical harmonic magnetic field models. It has a bunch of built in models from magnetized planets and a moon (Ganymede). This library is used by libjupitermag.

3.4.1 Installation

Compile and install in Linux and MacOS:

```
#clone the repo
git clone https://github.com/mattkjames7/libinternalfield

#cd into it
cd libjupitermag

#compile it
make
sudo make install
```

Or in Windows, run `compile.bat` to create `libinternalfield.dll`.

3.4.2 Usage

To use this library, the header should be included `include <internalfield.h>` and the code should be compiled with the `-linternalfield` flag in order to link to the library.

In C, we can use the `getModelFieldPointer()` to get a function pointer to the model we want to use, e.g.:

```
#include <stdio.h>
#include <internalfield.h>

int main() {

        printf("Testing C\n");

        /* try getting a model function */
        modelFieldPtr model = getModelFieldPtr("jrm33");
        double x = 10.0;
        double y = 10.0;
        double z = 0.0;
```

```
        double Bx, By, Bz;
        model(x,y,z,&Bx,&By,&Bz);

        printf("B = [%6.1f,%6.1f,%6.1f] nT at [%4.1f,%4.1f,%4.1f]\n",Bx,By,Bz,x,y,z);

        printf("C test done\n");

}
```

C++ can use the `internalModel` object, e.g.:

```
#include <internal.h>

int main() {
    /* set current model */
    internalModel.SetModel("jrm09");

    /* set intput and output coordinates to Cartesian */
    internalModel.SetCartIn(true);
    internalModel.SetCartOut(true);

    /* input position (cartesian)*/
    double x = 35.0;
    double y = 10.0;
    double z = -4.0;

    /* output field */
    double Bx, By, Bz;
    internalModel.Field(x,y,z,&Bx,&By,&Bz);
}
```

3.5 `vsmodel`: Python based Volland-Stern electric field model for Earth

This is a purely Python-based implementation of the Volland-Stern electric field model Volland1973,Stern1975.

3.5.1 Installation

Use `pip`:

```
pip3 install vsmodel --user
```

3.5.2 Usage

Electric field vectors can be determined using either cylindrical (`vsmodel.ModelE`) or Cartesian (`vsmodel.ModelCart`) coordinates (Solar Magnetic), e.g.:

```
import vsmodel

##### The simple model using Maynard and Chen ####
#the Cartesian model
Ex,Ey,Ez = vsmodel.ModelCart(x,y,Kp)

#the cylindrical model
Er,Ep,Ez = vsmodel.ModelE(r,phi,Kp)


#### The Goldstein et al 2005 version ####
#the Cartesian model, either by providing solar wind
#speed (Vsw) and IMF Bz (Bz), or the equivalent E field (Esw)
Ex,Ey,Ez = vsmodel.ModelCart(x,y,Kp,Vsw=Vsw,Bz=Bz)
```

```
Ex,Ey,Ez = vsmodel.ModelCart(x,y,Kp,Esw=Esw)

#the cylindrical model
Er,Ep,Ez = vsmodel.ModelE(r,phi,Kp,Vsw=Vsw,Bz=Bz)
Er,Ep,Ez = vsmodel.ModelE(r,phi,Kp,Esw=Esw)
```

where the Maynard1975 method uses the Kp index and the Goldstein2005 method uses Kp, solar wind speed and the z-component of the interplanetary magnetic field.

The electric field magnitude and $\mathbf{E} \times \mathbf{B}$ velocity can be plotted in the Earth's equatorial plane:

```
import vsmodel
import matplotlib.pyplot as plt

plt.figure(figsize=(9,8))
ax0 = vsmodel.PlotModelEq('E',Kp=1.0,Vsw=-400.0,Bz=-2.5,
                maps=[2,2,0,0],fig=plt,fmt='%4.2f',scale=[0.01,10.0])
ax1 = vsmodel.PlotModelEq('E',Kp=5.0,Vsw=-400.0,Bz=-2.5,
                maps=[2,2,1,0],fig=plt,fmt='%4.2f',scale=[0.01,10.0])
ax2 = vsmodel.PlotModelEq('V',Kp=1.0,Vsw=-400.0,Bz=-2.5,
                maps=[2,2,0,1],fig=plt,scale=[100.0,10000.0])
ax3 = vsmodel.PlotModelEq('V',Kp=5.0,Vsw=-400.0,Bz=-2.5,
                maps=[2,2,1,1],fig=plt,scale=[100.0,10000.0])
ax0.set_title('$K_p=1$; $E_{sw}=-1$ mV m$^{-1}$')
ax2.set_title('$K_p=1$; $E_{sw}=-1$ mV m$^{-1}$')
ax3.set_title('$K_p=5$; $E_{sw}=-1$ mV m$^{-1}$')
ax1.set_title('$K_p=5$; $E_{sw}=-1$ mV m$^{-1}$')
plt.tight_layout()
```

which would produce figure 3.2

3.6 JupiterMag: Python wrapper for Jovian field models

GitHub: https://github.com/mattkjames7/JupiterMag.git

Python wrapper for a collection of Jovian magnetic field models written in C++ (see libjupitermag).

This is part of a community code project : Magnetospheres of the Outer Planets Group Community Code

3.6.1 Requirements

For the Python code to run (without rebuilding the C++ backend), the following Python packages would be required:

- NumPy
- Matplotlib
- DateTimeTools
- RecarrayTools
- PyFileIO

All of which would be installed automatically if using `pip`.

On some systems, the shared object files would need rebuilding before they can be loaded and accessed using Python. Upon the first import of the `JupiterMag` module, if the shared object/DLL fails to load then it will attempt to use a local C++ compiler to rebuild the binaries.

Linux

JupiterMag was built and tested primarily using Linux Mint 20.3 (based on Ubuntu 20.04/Debian). To rebuild the code, ensure that `g++`, `make`, and `ld` are installed.

Windows

This has been tested on Windows 10 (64-bit), other versions may also work. Requires `g++` and `ld` to work (these can be provided by TDM-GCC). This may or may not work with other compilers installed.

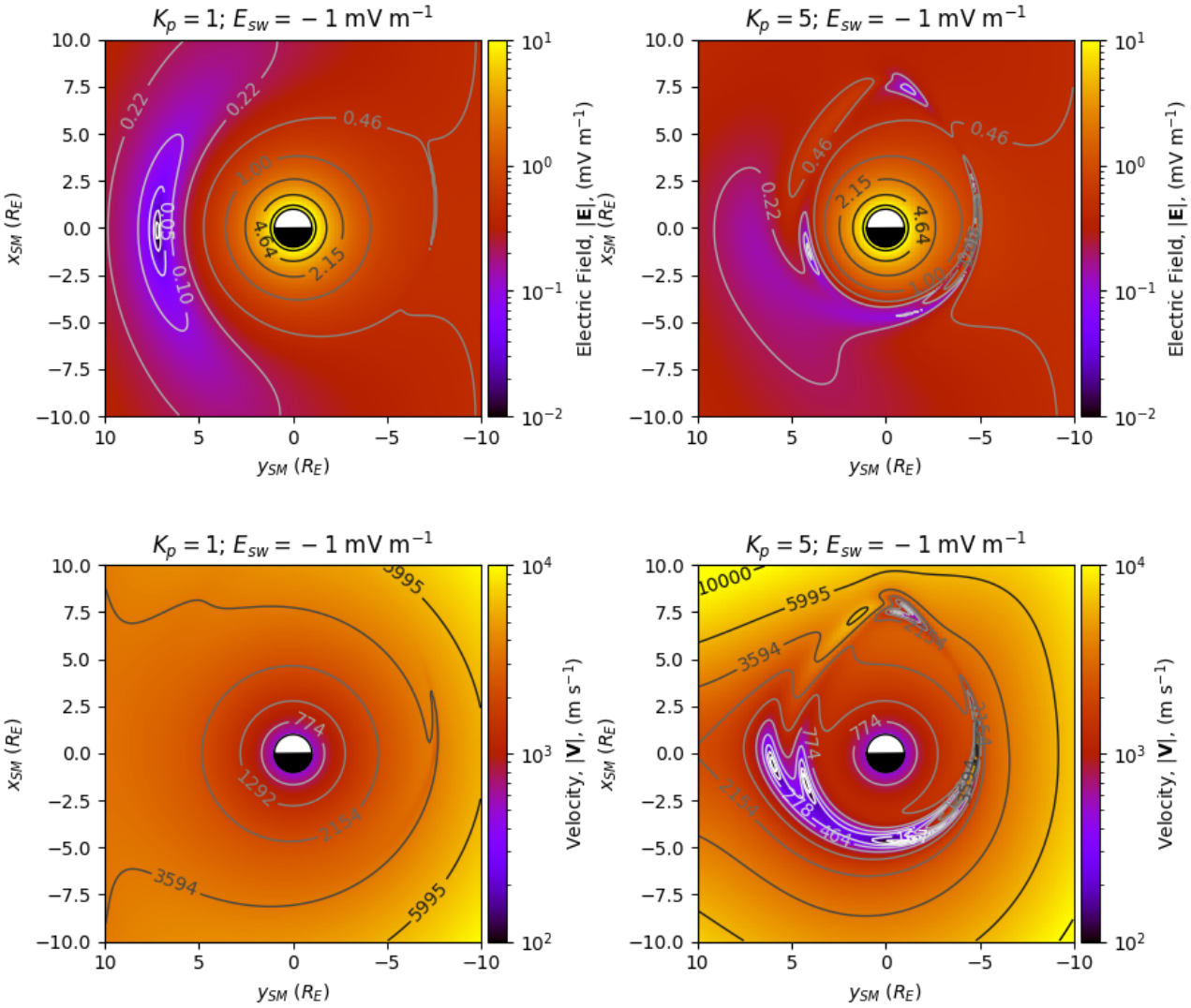


Figure 3.2: Volland-Stern electric field (top plots) and $\mathbf{E} \times \mathbf{B}$ velocity (bottom plots).

MacOS

This module has been tested on MacOS 11 Big Sur. It requires `g++`, `make`, and `libtool` to recompile (provided by Xcode).

3.6.2 Installation

Install using `pip3`:

```
pip3 install JupiterMag --user
```

Download the latest release (on the right → if you're viewing this on GitHub), then from within the directory where it was saved:

```
pip3 install JupiterMag-1.0.0-py3-none-any.whl --user
```

Or using this repo (replace "1.0.0" with the current version number):

```
#pull this repo
git clone https://github.com/mattkjames7/JupiterMag.git
cd JupiterMag

#update the submodule
git submodule update --init --recursive

#build the wheel file
python3 setup.py bdist_wheel
#the output of the previous command should give some indication of
#the current version number. If it's not obvious then do
# $ls dist/ to see what the latest version is
pip3 install dist/JupiterMag-1.0.0-py3-none-any.whl --user
```

I recommend installing `gcc` $\geq$ 9.3 (that's what this is tested with, earlier versions may not support the required features of C++).

This module should now work with both Windows and MacOS.

Update an Existing Installation

To update an existing installation:

```
pip3 install JupiterMag --upgrade --user
```

Alternatively, uninstall then reinstall, e.g.:

```
pip3 uninstall JupiterMag
pip3 install JupiterMag --user
```

3.6.3 Usage

Internal Field

A number of internal field models are included (see here for more information) and can be accessed via the `JupiterMag.Internal` submodule, e.g.:

```
import JupiterMag as jm

#configure model to use VIP4 in polar coords (r,t,p)
jm.Internal.Config(Model="vip4",CartesianIn=False,CartesianOut=False)
Br,Bt,Bp = jm.Internal.Field(r,t,p)

#or use jrm33 in cartesian coordinates (x,y,z)
jm.Internal.Config(Model="jrm33",CartesianIn=True,CartesianOut=True)
Bx,By,Bz = jm.Internal.Field(x,y,z)
```

All coordinates are either in planetary radii (x, y, z, r) or radians (t, p). All Jovian models here use $R_j = 71,492$ km.

External Field

Currently, the only external field source included is the Con2020 field (see here for the standalone Python code and here for more information on the C++ code used here as part of libjupitermag), other models could be added in the future.

This works in a similar way to the internal field, e.g.:

```
#configure model
jm.Con2020.Config(equation_type='analytic')
Bx,By,Bz = jm.Con2020.Field(x,y,z)
```

Tracing

Field line tracing can be done using the `TraceField` object, e.g.

```
import JupiterMag as jm

#configure external field model prior to tracing
#in this case using the analytic Con2020 model for speed
jm.Con2020.Config(equation_type='analytic')

#trace the field in both directions from a starting position
T = jm.TraceField(5.0,0.0,0.0,IntModel='jrm09',ExtModel='Con2020')
```

The above example will trace the field line from the Cartesian SIII position (5.0,0.0,0.0) (R_j) in both directions until it reaches the planet using the JRM09 internal field model with the Con2020 external field model. The object returned, `T`, is an instance of the `TraceField` class which contains the positions and magnetic field vectors at each step along the trace, along with some footprint coordinates and member functions which can be used for plotting.

A longer example below can be used to compare field traces using just an internal field model (JRM33) with both internal and external field models (JRM33 + Con2020):

```
import JupiterMag as jm
import numpy as np

#be sure to configure external field model prior to tracing
jm.Con2020.Config(equation_type='analytic')
#this may also become necessary with internal models in the future, e.g.
#setting the model degree

#create some starting positions
n = 8
theta = (180.0 - np.linspace(22.5,35,n))*np.pi/180.0
r = np.ones(n)
x0 = r*np.sin(theta)
y0 = np.zeros(n)
z0 = r*np.cos(theta)

#create trace objects, pass starting position(s) x0,y0,z0
T0 = jm.TraceField(x0,y0,z0,Verbose=True,IntModel='jrm33',ExtModel='none')
T1 = jm.TraceField(x0,y0,z0,Verbose=True,IntModel='jrm33',ExtModel='Con2020')

#plot a trace
ax = T0.PlotRhoZ(label='JRM33',color='black')
ax = T1.PlotRhoZ(fig=ax,label='JRM33 + Con2020',color='red')

ax.set_xlim(-2.0,15.0)
ax.set_ylim(-6.0,6.0)
```

The resulting objects T0 and T1 store arrays of trace positions and magnetic field vectors along with a bunch of footprints. The above code produces figure 3.3.

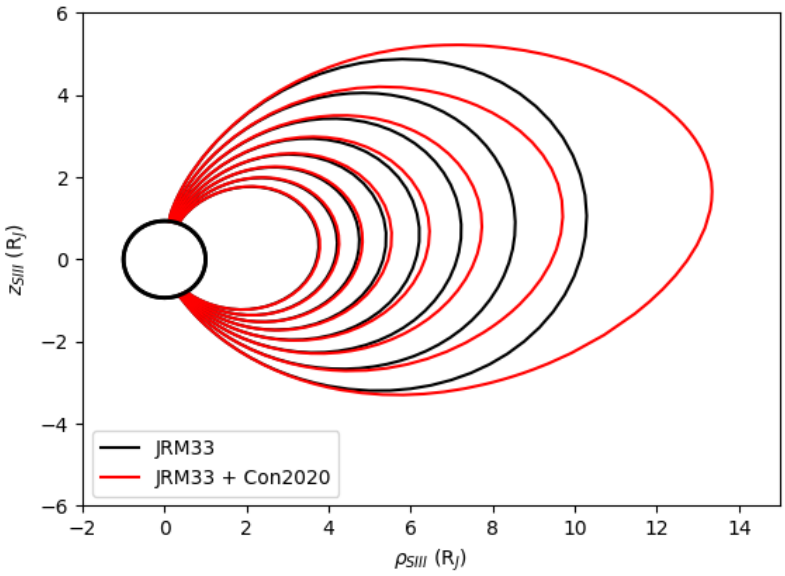


Figure 3.3: Comparison between traces using only the internal field (black) and traces also using a magnetodisc model (red).

3.7 libjupitermag: C++ library for field tracing in Jupiter's magnetosphere

GitHub: https://github.com/mattkjames7/libjupitermag.git

Code for obtaining magnetic field vectors and traces from within Jupiter's magnetosphere using various magnetic field models.

This is part of a community code project :
Magnetospheres of the Outer Planets Group Community Code
This module forms part of the JupiterMag package for Python.

3.7.1 Cloning and Building

This module requires a few submodules to be fetched, so the following command should clone everything:

```
git clone --recurse-sumodules https://github.com/mattkjames7/libjupitermag.git
```

This library requires `g++`, `make`, and `ld` (Linux) or `libtool` (Mac) in order to be compiled. On Windows, these tools can be provided by TDM-GCC.

To build in Linux and Mac, simply run

```
cd libjupitermag
make
#optionally install the library
sudo make install
```

where the installation defaults to `/usr/local` but can be changed using the `PREFIX` argument, e.g.:

```
sudo make install PREFIX=/usr
```

It can also be uninstalled:

```
make uninstall
```

Under Windows powershell/command line:

```
cd libjupitermag
compile.bat
```

or under Linux but building for Windows:

```
cd libjupitermag
make windows
```

After a successful build, a new library (`libjupitermag.so`) or DLL (`libjupitermag.dll`) should appear in the `lib/libjupitermag` directory.

3.7.2 Usage

The shared object library created by compiling this project should be accessible by various programming languages. This section mostly covers C++, other languages should be able to use the functions defined in the `extern "C"` section of the header file quite easily. For Python, it is straightforward to use `ctypes` to access this library, similarly, IDL could use the `CALL_EXTERNAL` function.

Linking to the library

Here is a very basic example of how to link to the code using C++ and print the version of the library:

```
/* test.cc */
#include <stdio.h>
#include <jupitermag.h>

int main() {
        /* simply print the version of the library */
        printf("libjupitermag version: $%d.%d.%d\n",
                        LIBJUPITERMAG_VERSION_MAJOR,
                        LIBJUPITERMAG_VERSION_MINOR,
                        LIBJUPITERMAG_VERSION_PATCH);
        return 0;
}
```

If the library was installed using `sudo make install`, then the library can be linked to during compiling time with:

```
g++ test.c -o test -ljupitermag
```

Otherwise, the header should be included using a relative or absolute path, e.g:

```
/* instead of this */
#include <jupitermag>
/* use something like this */
#include "include/jupitermag.h"
```

then compile, e.g.:

```
# absolute path
g++ test.cc -o test -L:/path/to/libjupitermag.so

# or relative path
g++ test.cc -o test -Wl,-rpath='$$ORIGIN/../lib/libjupitermag' -L ..lib/libjupitermag -ljupitermag
```

Calling Field Models

Internal field models can be called using the `InternalModel` object, e.g.:

```
#include <stdio.h>
#include <jupitermag.h>

int main () {
        /* create an instance of the object */
        InternalModel modelobj = InternalModel();

        /* set the model to use */
```

```
        modelobj.SetModel("jrm09");

        /* get the model vectors at some position */
        double x = 10.0, y = 0.0, z = 0.0;
        double Bx, By, Bz;
        modelobj.Field(x,y,z,&Bx,&By,&Bz);

        printf("B at [%f,%f,%f] = [%f,%f,%f]\n",x,y,z,Bx,By,Bz);
}
```

There are also simple functions for each of the models included in the library, see the table below.

Model	C String	Field Function	Reference
JRM33	`jrm33`	`jrm33Field`	Connerney et al., 2022
JRM09	`jrm09`	`jrm09Field`	Connerney et al., 2018
ISaAC	`isaac`	`isaacField`	Hess et al., 2017
VIPAL	`vipal`	`vipalField`	Hess et al., 2011
VIP4	`vip4`	`vip4Field`	Connerney 2007
VIT4	`vit4`	`vit4Field`	Connerney 2007
O4	`o4`	`o4Field`	Connerney 1981
O6	`o6`	`o6Field`	Connerney 2007
GSFC15evs	`gsfc15evs`	`gsfc15evsField`	Connerney 1981
GSFC15ev	`gsfc15ev`	`gsfc15evField`	Connerney 1981
GSFC13ev	`gsfc13ev`	`gsfc13evField`	Connerney 1981
Ulysses 17ev	`u17ev`	`u17evField`	Connerney 2007
SHA	`sha`	`shaField`	Connerney 2007
Voyager 1 17ev	`v117ev`	`v117evField`	Connerney 2007
JPL15ev	`jpl15ev`	`jpl15evField`	Connerney 1981
JPL15evs	`jpl15evs`	`jpl15evsField`	Connerney 1981
P11A	`p11a`	`p11aField`	
External Model			
Con 2020	`con2020`	`Con2020Field`	Connerney et al., 1981; Edwards et al., 2001; Connerney et al., 2020

Table 3.1: Internal and External Field Models

Field Tracing

Field tracing can be done using the `Trace` object, e.g.:

```
#include <stdio.h>
#include <jupitermag.h>
#include <vector>

int main () {
        /* set initial position to start trace from (this can be an array
                for multiple traces) */
        int n = 1;
        double x0 = 5.0;
        double y0 = 0.0;
        double z0 = 0.0;
        int nalpha = 1;
        double alpha = 0.0;

        printf("Create field function vector\n");
        /* store the function pointers for the components of the
        model to be included in the trace */
        std::vector<FieldFuncPtr> Funcs;

        /* internal model */
        Funcs.push_back(jrm09Field);
```

```
        /* external model */
        Funcs.push_back(Con2020Field);

        /* initialise the trace object */
        printf("Create Trace object\n");
        Trace T(Funcs);

        /* add the starting positions for the traces */
        printf("Add starting position\n");
        T.InputPos(n,&x0,&y0,&z0);

        /* configure the trace parameters, leaving this empty will
        use default values for things like minimum and maximum step size */
        printf("Set the trace parameters \n");
        T.SetTraceCFG();

        /* set up the alpha calculation - the angles (in degrees) of each
        polarization angle. This is generally used for ULF waves */
        printf("Initialize alpha\n");
        T.SetAlpha(nalpha,&alpha);

        /* Trace */
        printf("Trace\n");
        T.TraceField();

        /* trace distance, footprints, Rnorm */
        printf("Footprints etc...\n");
        T.CalculateTraceDist();
        T.CalculateTraceFP();
        T.CalculateTraceRnorm();

        /* calculate halpha for each of the polarization angles
           specified above*/
        printf("H_alpha\n");
        T.CalculateHalpha();
}
```

The above code traces along the magnetic field using the JRM09 internal and Con2020 external field models together. The trace coordinates and field vectors at each step can be obtained from the member variables `T.x_`, `T.y_`, `T.z_`, `T.Bx_`, `T.By_`, and `T.Bz_`, where each is a 2D array with the shape (`T.n_`,`T.MaxLen_`), where `T.n_` is the number of traces and `T.MaxLen_` is the maximum number of steps allowed in the trace. The number of steps taken in each trace is defined in the `T.nstep_` array.

3.8 con2020: Python implementation of Jupiter's magnetodisc model

Python implementation of the Connerney et al., 1981 and Connerney et al., 2020 Jovian magnetodisc model. This model provides the magnetic field due to a "washer-shaped" current near to Jupiter's magnetic equator. This model code uses either analytical equations from Edwards et al., 2001 or the numerical integration of the Connerney et al., 1981 equations to provide the magnetodisc field, depending upon proximity to the disc along z and the inner edge of the disc, r_0.

For the IDL implementation of this model, see: https://github.com/marissav06/con2020$_idl$

Or for Matlab: https://github.com/marissav06/con2020$_matlab$

A PDF documentation file is available here: con2020$_final_code_documentation_june9_2022.pdf$. It describes the Connerney current sheet model and general code development (equations used, numerical integration assumptions, accuracy testing, etc.). Details specific to the Python code are provided in this readme file.

These codes were developed by Fran Bagenal, Marty Brennan, Matt James, Gabby Provan, Marissa Vogt, and Rob Wilson, with thanks to Jack Connerney and Masafumi Imai. They are intended for use by the Juno science team and other members of the planetary magnetospheres community. Our contact information is in the documentation PDF file.

3.8.1 Installation

Install the module using `pip3`:

```
pip3 install --user con2020

#or if you have previously installed using this method
pip3 install --upgrade --user con2020
```

Or using this repo:

```
#clone the repo
git clone https://github.com/gabbyprovan/con2020
cd con2020

#EITHER create a wheel and install (X.X.X is the current version number)
python3 setup.py bdist_wheel
pip3 install --user dist/con2020-X.X.X-py3-none-any.whl

#or directly install using setup.py
python3 setup.py insall --user
```

3.8.2 Usage

To call the model, an object must be created first using `con2020.Model()`, where the default model parameters, model equations used or coordinate systems of input and output can be altered using keywords, e.g:

```
import con2020

#initialize a model object with default parameters
def_model = con2020.Model()

#initialize a model which uses spherical polar coordinates for input and output
sph_model = con2020.Model(CartesianIn=False,CartesianOut=False)

#initialize a model with custom parameters (longhand)
cust_model0 = con2020.Model(mu_i_div2__current_parameter_nT=150.0,
                                                    r0__inner_rj=9.5,
                                                d__cs_half_thickness_rj=3.1)

#equivalently, a custom parameter model (shorthand)
cust_model1 = con2020.Model(mu_i=150.0,r0=9.5,d=3.1)
```

Once a model object is initialized, the model field can be obtained by calling the member function `Field()` and supplying input coordinates as three scalars, or three arrays (all of which are in right-handed System III), e.g.:

```
#Example 1: the model at a single Cartesian position (all in Rj)
x = 5.0
y = 10.0
z = 6.0
Bcart = def_model.Field(x,y,z)
#Result:
Bxyz=[15.57977074, 36.88229249, 63.02051163] nT
#Calculated using the default con2020 model keywords and the hybrid approximation.

#Example 2: the model at an array of positions of spherical polar coordinates
r = np.array([10.0,20.0])                                    #radial distance in Rj
theta = np.array([30.0,35.0])*np.pi/180.0        #colatitude in radians
phi = np.array([90.0,95.0])*np.pi/180.0        #east longitude in radians
Bpol = sph_model.Field(r,theta,phi)
#Result:
Spherical polar Brtp =[63.32354453 ,31.15790459], [-21.01051861 , -6.86773727], [-3.61151705, -2.726260
```

```
Cartesian       Bxyz =[3.61151705, 1.6486016], [13.4661294,  12.43672946], [65.34505753, 29.46223351] n
#Calculated using the default con2020 model keywords and the hybrid approximation.
```

The output will be a `numpy.ndarray` with a shape `(n,3)`, where `n` is the number of input coordinates, `B[:,0]` corresponds to either `Bx` or `Br`; `B[:,1]` corresponds to `By` or `Btheta`; and `B[:,2]` corresponds to either `Bz` or `Bphi`. A full list of model keywords is shown below:

Keyword (long)	Keyword (short)	Default Value	Description
mu_i_div2__current_parameter_nT	mu_i	139.6*	Current sheet current density
i_rho__radial_current_MA	i_rho	16.7*	†Radial current intensity in M from Connerney et al 2020.
r0__inner_rj	r0	7.8	Inner edge of the current sheet
r1__outer_rj	r1	51.4	Outer edge of the current shee
d__cs_half_thickness_rj	d	3.6	Current sheet half thickness in
xt__cs_tilt_degs	xt	9.3	Tilt angle of the current sheet
xp__cs_rhs_azimuthal_angle_of_tilt_degs	xp	155.8	(Right-Handed) Longitude tow
equation_type		'hybrid'	Which method to use, can be: 'analytic' - use only the ana 'integral' - numerically inte 'hybrid' - a combination of a
error_check		True	Check errors on inputs the the
CartesianIn		True	If True (default) then the inpu
CartesianOut		True	If True the output magnetic fi
azfunc		'connerney'	Which model to use for the az
DeltaRho		1.0	Scale length over which smoot
DeltaZ		0.1	Scale length over which smoot
g		417659.3836476442	§Magnetic dipole parameter, n
w0_open		0.1	§Ratio of plasma to Jupiter's a
w0_om		0.35	§Ratio of plasma to Jupiter's a
thetamm		16.1	§Colatitude of the centre of th
dthetamm		0.5	§Colatitude range over which t
thetaoc		10.716	§Colatitude of the centre of th
dthetaoc		0.125	§Colatitude range of the open-

*Default current densities used here are averages provided in Connerney et al., 2020 (see Figure 6), but can vary from one pass to the next. Table 2 of Connerney et al., 2020 provides a list of both current densities for 23 out of the first 24 perijoves of Juno.

† This is only applicable for the Connerney et al., 2020 model for B_ϕ.

§ These parameters are used to configure the L-MIC model for B_ϕ.

The `con2020.Test()` function should produce figure 3.4:

3.9 `libcon2020`: C++ implementation of Jupiter's magnetodisc model

C++ implementation of the Connerney et al., 1981 and Connerney et al., 2020 Jovian magnetodisc model. This model provides the magnetic field due to a "washer-shaped" current disc near to Jupiter's magnetic equator. The model uses the analytical equations from Edwards et al., 2001 or Connerney et al., 1981; or the numerical integration of the Connerney et al., 1981 equations to provide the magnetic field vectors due to the azimuthal current. This code also implements the Connerney et al., 2020 radial current and the Leicester magnetosphere-ionosphere coupling (L-MIC, Cowley et al., 2005, 2008) models which provide the azimuthal component of the magnetic field.

This is part of `libjupitermag`, which is part of a greater effort to provide community code for the Jovian magnetosphere:

`Magnetospheres of the Outer Planets Group Community Code`

3.9.1 Building libcon2020

To build this library in Linux or Mac OS:

```
#clone this repo
git clone https://github.com/mattkjames7/libcon2020.git
```

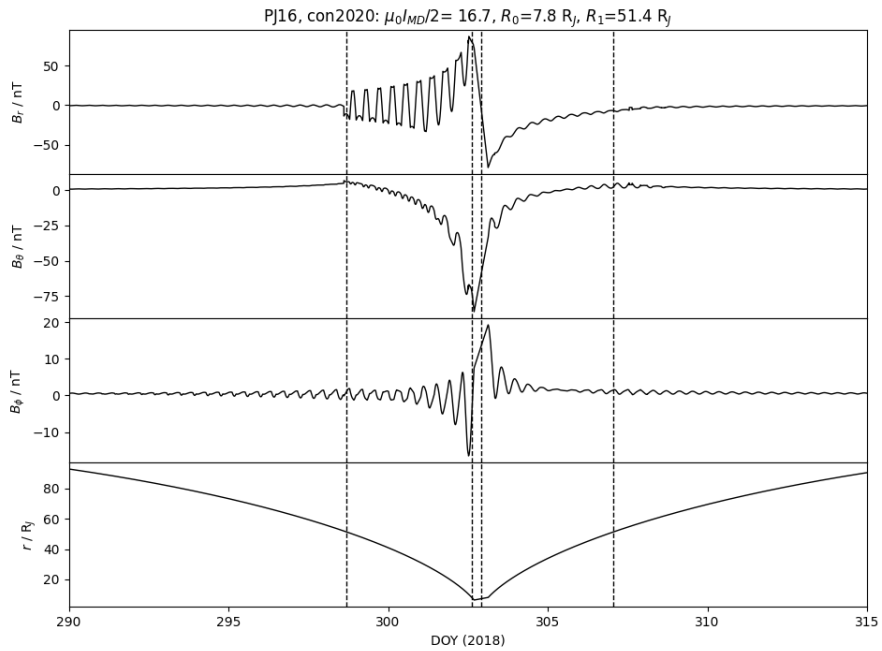


Figure 3.4: Test of `con2020` code on a Juno orbit.

```
cd libcon2020

#build
make

#optionally install it system wide
sudo make install
```

In Windows:

```
git clone https://github.com/mattkjames7/libcon2020.git
cd libcon2020

.\compile.bat
```

With a system wide installation, the compiler and linker will be able to locate the library and its header, otherwise absolute paths must be provided for linking and including. In Windows, there is an experimental script `install.bat` which will copy the DLL and headers to folders within the `C:\TDC-GCC-64\` directory. This is experimental; instead, it might be better to copy the headers and the DLL to the root directory of the executable linked to it.

Uninstallation can be achieved in Linux and Mac using `sudo make uninstall`.

3.9.2 Usage

Linking to and Including libcon2020

If a system-wide installation is successful, then the library may be linked to simply by including the `-lcon2020` flag while compiling/linking. Otherwise, the path to the library must also be included, e.g. `-L /path/to/lib/directory -lcon2020`. In Windows, the DLL should be placed in the root directory of the executable linked to it.

This library includes a header file `include/con2020.h` which is compatible with both C and C++. This header contains the full set of function and class prototypes for use with C++; it also includes C-compatible wrapper functions. The wrapper functions in the header file would also provide the easiest ways to link other languages to the library such as Python, IDL, and Fortran.

If the library was installed system-wide, then the headers may be included using `#include <con2020.h>`. Otherwise, a relative or absolute path to the headers must be used, e.g. `#include "path/to/con2020.h"`.

C++ usage

This section briefly describes some C++ specific examples for using the `libcon2020` library, while the following section is also somewhat applicable.

Access the model using the `Con2020` class:

```
/* contents of cppexample.cc */
#include <stdio.h>
#include <con2020.h>

int main () {
        /* create an instance of the model */
        Con2020 model;

        /* set coordinate system to be Cartesian SIII (default) */
        model.SetCartIn(true);
        model.SetCartOut(true);

        /* create some variables to store a field vector in,
         * note that positions are in units of Rj */
        double x = 11.0;
        double y = 5.0;
        double z = -10.0;
        double Bx, By, Bz;

        /* call the model */
        model.Field(x,y,z,&Bx,&By,&Bz);
        printf("B=[%5.1f,%5.1f,%5.1f] nT at [%4.1f,%4.1f,%4.1f] Rj\n",Bx,By,Bz,x,y,z);

        /* alternatively obtain an array of field vectors in spherical polar coords */
        model.SetCartIn(false);
        model.SetCartOut(false);
        double r[] = {5.0,10.0,15.0};
        double theta[] = {1.0,1.5,2.0};
        double phi[] = {0.0,0.1,0.2};
        double Br[3], Bt[3], Bp[3];

        model.Field(3,r,theta,phi,Br,Bt,Bp);
        int i;
        for (i=0;i<3;i++) {
                printf("B=[%5.1f,%5.1f,%5.1f] nT at r = %4.1f Rj, theta = %4.1f rad, phi = %4.1f rad\n"
        }

        return 0;
}
```

In the example above, the model can be configured by using class member functions (e.g., `Con2020::SetCartIn()`), see the table below for a full list of configurable parameters. The `Con2020::Field()` function is overloaded, so it can either accept a single input position to provide a single field vector or can accept an array of positions to provide an array of field vectors. Compile and run the above example using

```
g++ cppexample.cc -o cppexample -lcon2020
./cppexample
```

Other Languages

In other languages, it is easier to run the model code by using the wrapper functions listed in both `con2020.h`. For example, in C:

```
/* contents of cexample.c */
#include <stdio.h>
#include <stdbool.h>
```

```
#include <con2020.h>

int main() {

        /* we can obtain a single field vector like this,
         * using the default model parameters */
        double x = 10.0;
        double y = 20.0;
        double z = 5.0;
        double Bx, By, Bz;
        Con2020Field(x,y,z,&Bx,&By,&Bz);
        printf("B=[%5.1f,%5.1f,%5.1f] nT at [%4.1f,%4.1f,%4.1f] Rj\n",Bx,By,Bz,x,y,z);

        /* or using arrays */
        double xa[] = {10.0,20.0,30.0};
        double ya[] = {5.0,10.0,15.0};
        double za[] = {10.0,10.0,10.0};
        double Bxa[3], Bya[3], Bza[3];
        Con2020FieldArray(3,xa,ya,za,Bxa,Bya,Bza);
        int i;
        for (i=0;i<3;i++) {
                printf("B=[%5.1f,%5.1f,%5.1f] nT at [%4.1f,%4.1f,%4.1f] Rj\n",
                                        Bxa[i],Bya[i],Bza[i],xa[i],ya[i],za[i]);
        }

        /* we can retrieve the current model parameters */
        double mui, irho, r0, r1, d, xt, xp, DeltaRho, DeltaZ, g, w0_open,
                        w0_om, thetamm, dthetamm, thetaoc, dthetaoc;
        bool Edwards, ErrChk, CartIn, CartOut, smooth;
        char eqtype[16];
        char azfunc[16];
        GetCon2020Params(&mui,&irho,&r0,&r1,&d,&xt,&xp,eqtype,&Edwards,&ErrChk,
                                        &CartIn,&CartOut,&smooth,&DeltaRho,&DeltaZ,&g,azfunc,
                                        &w0_open,&w0_om,&thetamm,&dthetamm,&thetaoc,&dthetaoc);

        /* these parameters may be edited and passed back to the model */
        irho = 0.0;
        strcpy(eqtype,"analytic");
        SetCon2020Params(mui,irho,r0,r1,d,xt,xp,eqtype,Edwards,ErrChk,
                                        CartIn,CartOut,smooth,DeltaRho,DeltaZ,g,azfunc,
                                        w0_open,w0_om,thetamm,dthetamm,thetaoc,dthetaoc);
}
```

Compile and run using:

```
gcc cexample.c -o cexample -lcon2020
./cexample
```

3.9.3 Model Parameters

This table lists all of the configurable parameters currently included in the code.

Parameter	Default	Con2020 Member Functions		Description
mui	139.6	SetAzCurrentParameter()	GetAzCurrentParameter()	Azimuthal current she eter, nT.
irho	16.7	SetRadCurrentParameter()	GetRadCurrentParameter()	Radial current intensit
r0	7.8	SetR0()	GetR0()	Inner edge of the curr R_J.
r1	51.4	SetR1()	GetR1()	Outer edge of the curr R_J.
d	3.6	SetCSHalfThickness()	GetSCHalfThickness()	Half thickness of th sheet, R_J.
xt	9.3	SetCSTilt()	GetCSTilt()	Tilt angle of the cur away from the SIII z-a
xp	155.8	SetCSTiltAzimuth()	GetCSTiltAzimuth()	Right-handed longitud which the current shee °.
eqtype	"hybrid"	SetEqType()	GetEqType()	Set what method to us "analytic" - use anal tions "integral" - use fu equations "hybrid" - use a comb both
Edwards	true	SetEdwardsEqs()	GetEdwardsEqs()	Switch between the E al., 2001 and Conner 1981 analytical equati
ErrChk	true	SetErrCheck()	GetErrChk()	Check for errors on the Con2020::Field(), se for a slightly risky spe
CartIn	true	SetCartIn()	GetCartIn()	If true, then input c will be assumed to be S sian (in units of R_J), spherical polar coordi units of R_J; θ and ϕ i
CartOut	true	SetCartOut()	GetCartOut()	If true, then output fi will be in Cartesian S nates, otherwise they ented such that the thr nents are radial, merid azimuthal.
smooth	true	SetSmooth()	GetSmooth()	Use Stan's tanh-based to smooth over the boundaries in the ρ dir across $\pm d$ in the z dire
DeltaRho	1.0	SetDeltaRho()	GetDeltaRho()	Scale length over whic ing is done in the ρ dir
DeltaZ	0.1	SetDeltaZ()	GetDeltaZ()	Scale length over whic ing is done in the z di
g	417659.3836476442	SetG()	GetG()	Magnetic dipole paran
azfunc	"connerney"	SetAzimuthalFunc()	GetAzimuthalFunc()	Set the method to use late the azimuthal fie the radial component rent: "connerney" - use th ney et al., 2020 azim model "lmic" - use the L-M (Connerney et al., 200
w0_open	0.1	SetOmegaOpen()	GetOmegaOpen()	Ratio of plasma to Ju gular velocity on open
w0_om	0.35	SetOmegaOM()	GetOmegaOM()	Ratio of plasma to Ju gular velocity in the c netosphere.
thetamm	16.1	SetThetaMM()	GetThetaMM()	Colatitude of the cen middle magnetospher the plasma transitions tating to sub-corotatin

3.10 jrm33: The JRM33 model in Python

3.10.1 Installation

Install using `pip`:

```
pip3 install jrm33 --user
```

Or by cloning this repo:

```
git clone https://github.com/mattkjames7/jrm33.git
cd jrm09

# EITHER create a wheel and install (replace X.X.X with the version number):
python3 setup.py bdist_wheel
pip3 install dist/jrm33-X.X.X-py3-none-any.whl --user

% OR install directly using setup.py
python3 setup.py install --user
```

3.10.2 Usage

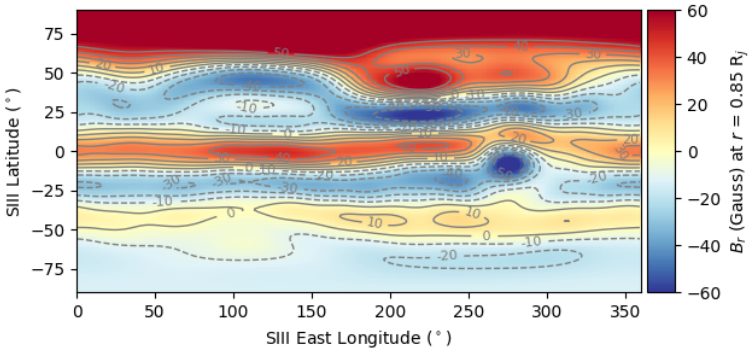
The model accepts right-handed System III coordinates either in Cartesian form (`jrm33.ModelCart()`) or in spherical polar form (`jrm33.Model()`), e.g.:

```
import jrm33

# get some Cartesian field vectors (Deg keyword is optional)
Bx, By, Bz = jrm33.ModelCart(x, y, z, Deg=13)

# or spherical polar ones
Br, Bt, Bp = jrm33.Model(r, theta, phi, Deg=13)
```

Please read the docstrings for `jrm33.Model()` and `jrm33.ModelCart()` using `help` or `?` e.g. `help(jrm33.Model)`. There is also a test function which requires `matplotlib` to be installed:

```
# evaluate the model at some R
jrm33.Test(R=0.85)
```

which produces this (based on figure 4 of Connerney et al. 2018):



3.11 jrm09: The JRM09 model in Python

3.12 Installation

Install using `pip`:

```
pip3 install jrm09 --user
```

Or by cloning this repo:

```
git clone https://github.com/mattkjames7/jrm09.git
cd jrm09

# EITHER create a wheel and install (replace X.X.X with the version number):
python3 setup.py bdist_wheel
pip3 install dist/jrm09-X.X.X-py3-none-any.whl --user

# OR install directly using setup.py
python3 setup.py install --user
```

3.13 Installation

Install using `pip`:

```
pip3 install jrm09 --user
```

Or by cloning this repo:

```
git clone https://github.com/mattkjames7/jrm09.git
cd jrm09

% EITHER create a wheel and install (replace X.X.X with the version number):
python3 setup.py bdist_wheel
pip3 install dist/jrm09-X.X.X-py3-none-any.whl --user

% OR install directly using setup.py
python3 setup.py install --user
```

3.14 Usage

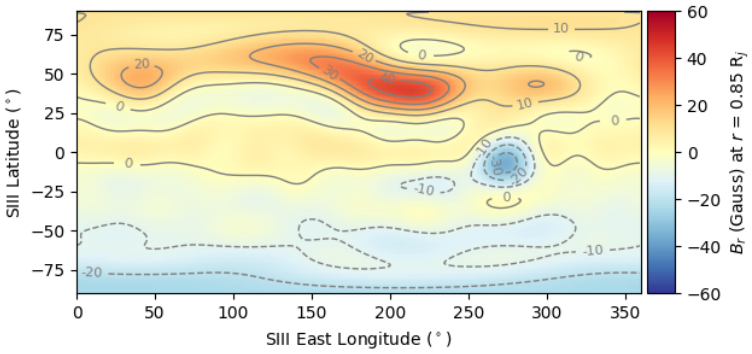
The model accepts right-handed System III coordinates either in Cartesian form (`jrm09.ModelCart()`) or in spherical polar form (`jrm09.Model()`), e.g.:

```
import jrm09

% get some Cartesian field vectors (MaxDeg keyword is optional)
Bx, By, Bz = jrm09.ModelCart(x, y, z, MaxDeg=10)

% or spherical polar ones
Br, Bt, Bp = jrm09.Model(r, theta, phi, MaxDeg=10)
```

Please read the docstrings for `jrm09.Model()` and `jrm09.ModelCart()` using `help` or `?` e.g. `help(jrm09.Model)`. There is also a test function which requires `matplotlib` to be installed:

```
#evaluate the model at some R
jrm09.Test(R=0.85)
```

which produces this (based on figure 4 of Connerney et al. 2018):



3.15 vip4model: The VIP4 model in Python

3.15.1 Installation

Install using `pip`:

```
pip3 install vip4model --user
```

Or by cloning this repo:

```
git clone https://github.com/mattkjames7/vip4model.git
cd vip4model

# EITHER create a wheel and install (replace X.X.X with the version number):
python3 setup.py bdist_wheel
pip3 install dist/vip4model-X.X.X-py3-none-any.whl --user

# OR install directly using setup.py
python3 setup.py install --user
```

3.15.2 Usage

The model accepts right-handed System III coordinates either in Cartesian form (`vip4model.ModelCart()`) or in spherical polar form (`vip4model.Model()`), e.g.:

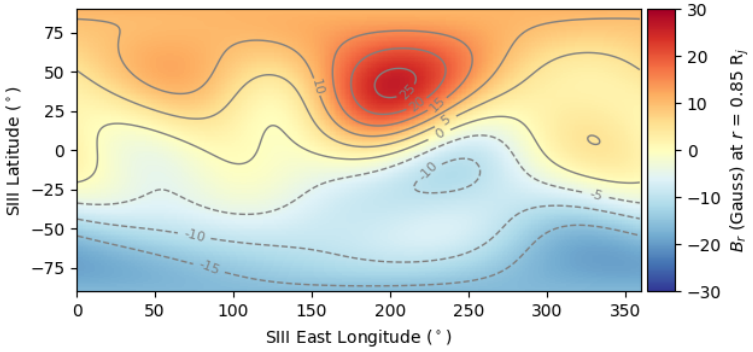
```
import vip4model

# get some Cartesian field vectors (MaxDeg keyword is optional)
Bx, By, Bz = vip4model.ModelCart(x, y, z, MaxDeg=4)

# or spherical polar ones
Br, Bt, Bp = vip4model.Model(r, theta, phi, MaxDeg=4)
```

Please read the docstrings for `vip4model.Model()` and `vip4model.ModelCart()` using `help` or `?` e.g. `help(vip4model.Model)`.

There is also a test function which requires `matplotlib` to be installed:

```
# evaluate the model at some R
vip4model.Test(R=0.85)
```

which produces this (based on figure 4 of Connerney et al. 2018):


SIII Latitude (°)
SIII East Longitude (°)
B_r (Gauss) at r = 0.85 R_J
75
50
25
0
−25
−50
−75
0
50
100
150
200
250
300
350
30
20
10
0
−10
−20
−30
10
25
15
5
0
-10
-5
-15

Chapter 4

Spacecraft Data

4.1 Arase: Download and read Arase data

4.1.1 Installation

Install from PyPI:

```
pip3 install Arase --user
```

or

```
python3 -m pip install Arase --user
```

Set the ARASE_PATH variable by placing the following at the end of ~/.bashrc:

```
export ARASE_PATH=/path/to/arase/data
```

4.1.2 Downloading Data

Most instrument data can be downloaded using the DownloadData function contained in the instruments sub-module, e.g.:

```
Arase.XXX.DownloadData(L, prod, Date=Date, Overwrite=Overwrite)
```

where XXX can be replaced with the instrument names: HEP, LEPe, LEPi, MEPe, MEPi, MGF or XEP. L is an integer and prod is a string which correspond to the level and data product provided by the instrument, respectively (see the table in "Current Progress"). Date determines the range of dates to download data for. The Date keyword can be a single date, a list of specific dates to download, or a 2 element list defining the start and end dates (by default Date = [20170101, 20200101]). Overwrite will force the routine to overwrite existing data.

This method will work for PWE data:

```
Arase.PWE.DownloadData(subcomp, L, prod, Date=Date, Overwrite=Overwrite)
```

where subcomp is the sub-component of the instrument (see table below).

To download the position data:

```
Arase.Pos.DownloadData(prod, Date=Date, Overwrite=Overwrite)
```

where prod is either 'l3' or 'def'. The 'def' option is needed for position-related functions elsewhere in the Arase module.

4.1.3 Position and Tracing

1. Download position data:

```
Arase.Pos.DownloadData('def')
```

2. Convert to a binary format (this allows for quicker reading):

```
Arase.Pos.ConvertPos()
```

3. Save field traces:

```
Arase.Pos.SaveFieldTraces(Model=Model, StartDate=StartDate, EndDate=EndDate)
```

where `Model` is either `'T89'`, `'T96'`, `'T01'` or `'TS05'` (`'T96'` by default). `StartDate` and `EndDate` are the start and end dates to perform traces for, both are integers of the format `yyymmdd`.

4. To read the position data:

```
pos = Arase.Pos.GetPos()
```

5. To read the traces:

```
tr = Arase.Pos.ReadFieldTraces(Date)
```

4.1.4 Reading Data

MGF Data

```
data = Arase.MGF.ReadMGF(Date)
```

This returns a `numpy.recarray` object which contains the time-series data. The `Date` argument may be a single date, a list of dates, or a 2 element `list` of dates defining the start and end date to load.

Particle Omni-directional Spectra

```
data = Arase.LEPe.ReadOmni(Date)
```

For other instruments, replace `LEPe` with one of the following: `LEPi`, `MEPe`, `MEPi`, `HEP` or `XEP`. `data` is a dictionary which will contain dates, times, energy bins, and instances of the `Arase.Tools.PSpecCls` object. The `PSpecCls` object contains all of the spectral information stored within it and is usually identified by the dictionary key containing `'Flux'`. The `PSpecCls` object has an in-built method for plotting the spectrograms, e.g.:

```
data['eFlux'].Plot()
```

will plot the electron flux spectrogram from the LEPe data loaded above. To list the keys of a dictionary, use `list(data.keys())`.

Combined Particle Spectra

Two functions are available which will load the data for multiple instruments at the same time.

For electrons:

```
E = Arase.Electrons.ReadOmni(Date)
```

and for ions:

```
H, He, O = Arase.Ions.ReadOmni(Date)
```

where `E`, `H`, `He`, and `O` are all instances of `SpecCls`.

Single Spectra

The `SpecCls` object has the ability to return single spectra, e.g.:

```
import Arase
import matplotlib.pyplot as plt

# read in the electrons - this should work with any SpecCls object
spec = Arase.Electrons.ReadOmni(Date)

# for the energy bins and particle flux data
e, dJdE, _ = spec.GetSpectrum(Date, ut)

# for velocity and phase space density
v, f, _ = spec.GetSpectrum(Date, ut, xparam='V', yparam='PSD')
```

```
# or to plot
plt.figure(figsize=(8, 4))
ax0 = spec.PlotSpectrum(Date, ut, xparam='E', yparam='Flux', Split=True, fig=plt, maps=[2, 1, 0
ax1 = spec.PlotSpectrum(Date, ut, xparam='V', yparam='PSD', Split=True, fig=plt, maps=[2, 1, 1,
plt.tight_layout()

# for more information, read the docstrings:
spec.GetSpectrum?
spec.PlotSpectrum?
```

3D Particle Spectra

These data are not currently placed into an object like `PSpecCls`. For instruments which provide 3D spectra, there is a function `Read3D` which will simply read the CDF file for a given date and list all of the data and corresponding metadata into two dictionaries, e.g.:

```
data, meta = Arase.LEPe.Read3D(Date)
```

Pitch Angle Distributions

For particle instruments with 3D flux data, there is a method to convert these to pitch angle distributions (PADs). The PADs are calculated using the MGF data and the elevation/azimuth angles of the instruments in GSE coordinates where provided in the level 2 `3dflux` data products. It was possible to compare this method to the angles provided by the level 3 `3dflux` product from the MEPe instrument, and almost all pitch angles were within about 1-2 degrees. **WARNING: these data should be used with caution - they may not be correct.**

To store the PADs:

```
import Arase
Arase.LEPe.SavePADs(Date, na=18, Overwrite=False, DownloadMissingData=True, DeleteNewData=True,
```

The above code will bin up the 3D LEPe fluxes from a single date into `na` pitch angle bins (always in the range 0 to 180 degrees). The `Overwrite` keyword will force the overwriting of previously created PAD files. `DownloadMissingData` will download any missing `3dflux` data and MGF data. `DeleteNewData` will delete the newly downloaded `3dflux` data after creating the PAD data because some of the `3dflux` files are ¿ 500 MB.

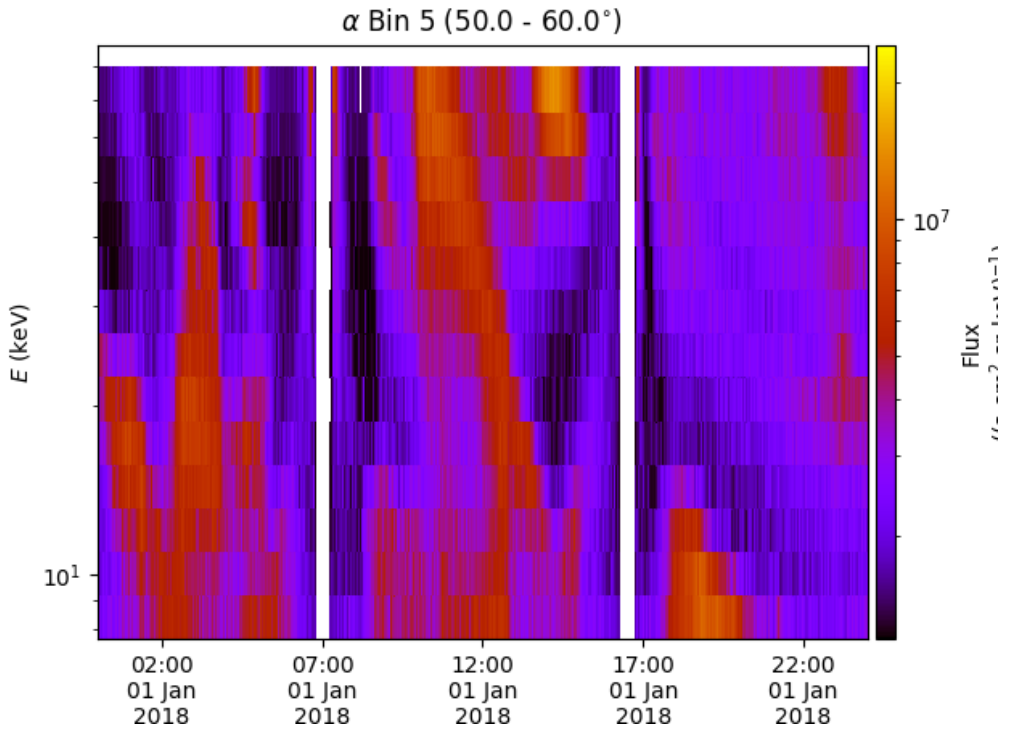
To read PADs:

```
pad = Arase.LEPe.ReadPAD(Date, SpecType, ReturnSpecObject=True)
```

This will read the PAD spectra from a single date for a given `SpecType` (e.g. `'eFlux'` or `'H+Flux'`, depending on the instrument). The returned object will either be a `dict` containing just the data if `ReturnSpecObject=False`, or a `Arase.Tools.PSpecPADCls` object if `ReturnSpecObject=True`. The `PSpecPADCls` object allows the plotting of spectrograms, 1D spectra, and 2D spectra.

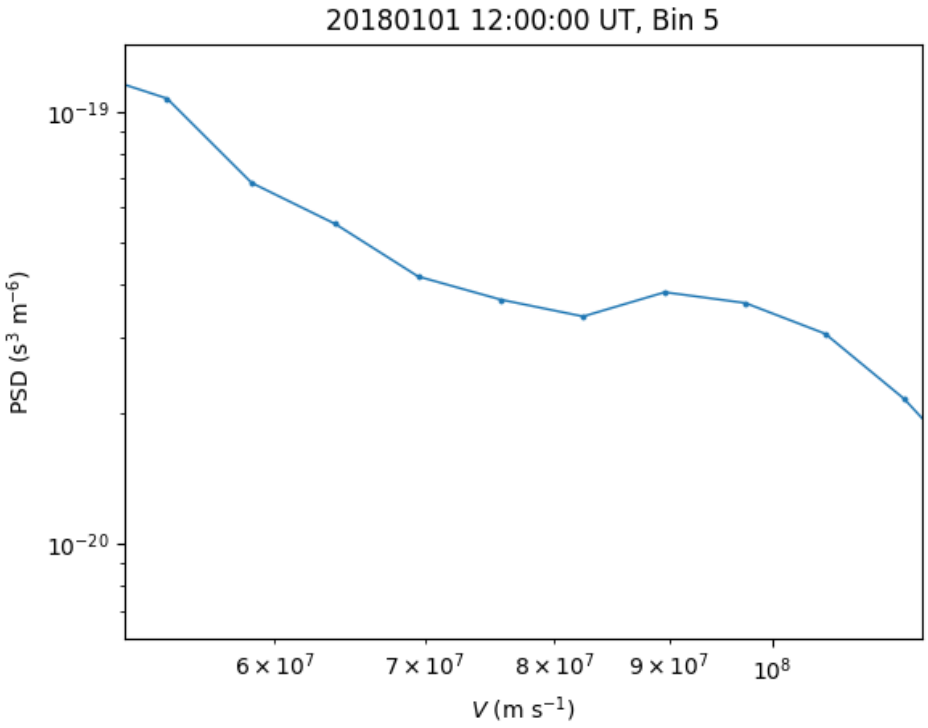
For a spectrogram of a specific pitch angle bin:

```
pad = Arase.MEPe.ReadPAD(20180101, 'eFlux')
pad.PlotSpectrogram(Bin=5)
```



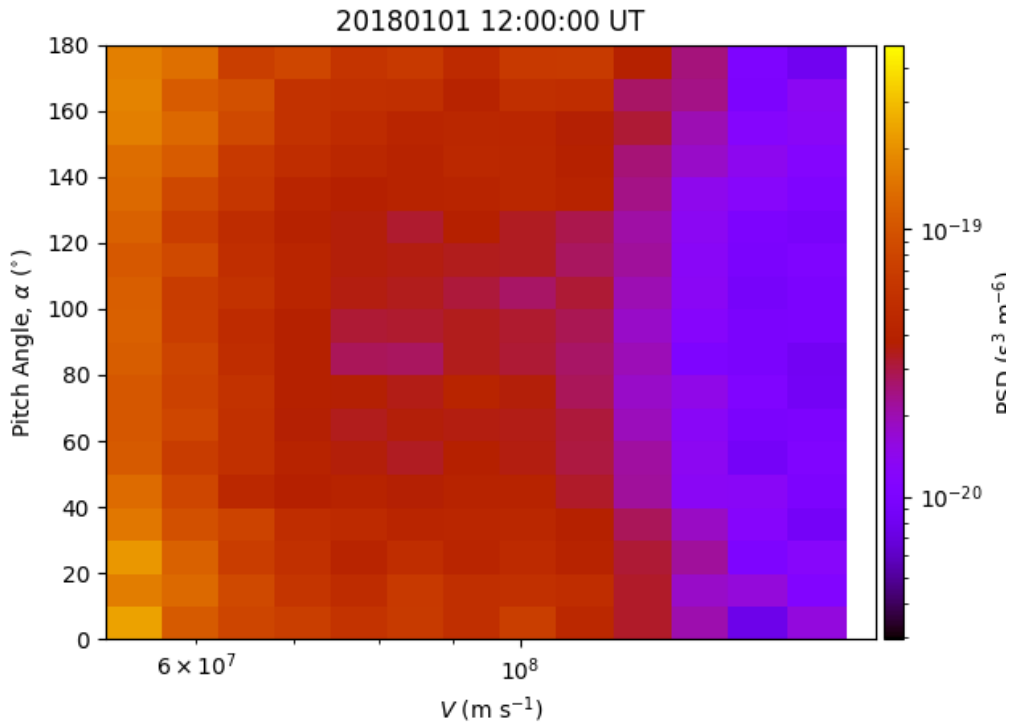
Or a 1D spectrum:

```
pad.PlotSpectrum1D(12.0, Bin=5, xparam='V', yparam='PSD')
```



Or a 2D spectrum:

```
pad.PlotSpectrum2D(12.0, xparam='V', zparam='PSD')
```



4.1.5 Current Progress

Instrument	Subcomponent	Level	Product	Download	Read	Plot
HEP		2	omniflux			
LEPe		2	omniflux			
LEPe		2	3dflux		×	×
LEPi		2	omniflux			
LEPi		2	3dflux		×	×
MEPe		2	omniflux			
MEPe		2	3dflux		×	×
MEPe		3	3dflux		×	×
MEPi		2	omniflux			
MEPi		2	3dflux		×	
MEPi		3	3dflux			×
MGF		2	8sec			×
PWE	efd	2	spec			
PWE	hfa	2	high			
PWE	hfa	2	low			
PWE	hfa	3				×
PWE	ofa	2	complex	×	×	×
PWE	ofa	2	matrix	×	×	×
PWE	ofa	2	spec		×	×
XEP		2	omniflux			

- - Works
- × - Not working yet. In the case of 3D data, a `SpecCls3D` object needs to be written. For MGF and level 3 hfa data, it's a simple case of plotting a line.
- - Probably works, but have no access to the data to be able to test it.
- × - Currently, 3D spectra can only be read into dictionaries as a `SpecCls3D` object is needed.

4.2 RBSP: Download and read Van Allen Probe data

Some tools for loading RBSP (Van Allen Probe) data.

4.2.1 Installation

Firstly, install the Python wheel package:

```
pip3 install wheel --user
```

Clone this repo, build and install (swap x.x.x for the current version):

```
git clone https://github.com/mattkjames7/RBSP.git
cd RBSP

#build the wheel
python3 setup.py bdist_wheel

#install the package just built
pip3 install dist/RBSP-0.0.1-py3-none-any.whl --user
```

4.2.2 Submodules

This is a list of submodules contained within this package.

- `ECT` (see documentation in `doc/ECT.md`)
- `EFW` (see documentation in `doc/EFW.md`)
- `EMFISIS` (see documentation in `doc/EMFISIS.md`)
- `Fields` (see documentation in `doc/Fields.md`)
- `Pos` (see documentation in `doc/Pos.md`)
- `RBSPICE` (see documentation in `doc/RBSPICE.md`)
- `RPS` (see documentation in `doc/RPS.md`)
- `VExB` (see documentation in `doc/VExB.md`)

4.2.3 ECT - Energetic Particle, Composition, and Thermal Plasma Suite

The overview of this instrument suite can be found in Spence et al., 2013.
ECT contains the following instruments:

- Helium, Oxygen, Proton, and Electron (HOPE) Mass Spectrometer (Funsten et al., 2013)
- Magnetic Electron Ion Spectrometer (MagEIS, Blake et al., 2013)
- Relativistic Electron-Proton Telescope (REPT, Baker et al., 2013)

List of Functions

The following functions are all called from within the `ECT` submodule, e.g.: `RBSP.ECT.DownloadData()`

Function Name	Description	Section
`DownloadData()`	Download latest data files.	
`ReadCDF()`	Read a downloaded CDF file.	
`DataAvailability()`	Checks what dates have data.	
`DeleteDate()`	Deletes data from a specific date.	
`RebuildDataIndex()`	Scan the downloaded data and rebuild the index file.	
`ReadHOPESA()`	Read the HOPE Spin-Averaged data into a `PSpecCls` object.	
`ReadHOPEMoments()`	Read the HOPE moments.	
`ReadHOPEOmni()`	Read the omnidirectional HOPE data into a `PSpecCls` object.	
`SaveIonMoments()`	Save the cold ion moments.	
`ReadIonMoments()`	Read the cold ion moments.	
`MomentAvailability()`	Check what dates there are moments calculated for.	
`CalculateIonMoments()`	Calculate the low energy ion moments.	
`PlotMoments()`	Plot moments.	
`PlotDensity()`	Plot density.	
`PlotTemp()`	Plot the temperature.	
`PlotMav()`	Plot the average ion mass.	

Downloading Data

Data from HOPE, MagEIS, and REPT can all be downloaded using the `DownloadData()` function. The `sc`, `Inst`, and `L` keywords determine which probe ('a' or 'b'), instrument, or level of data to download. To limit the time period over which to download data, set the `Date` keyword to a 2-element list containing the start and end dates in the format `yyyymmdd`.

Inst	L
'hope'	'l2.sectors'
'hope'	'l2.spinaverage'
'hope'	'l3.moments'
'hope'	'l3.pitchangle'
'mageis'	'l2'
'mageis'	'l3'
'rept'	'l2'
'rept'	'l3'

Data is stored in `$RBSP_PATH/ECT/Inst/L/sc/` (e.g., `$RBSP_PATH/ECT/hope/l2.sectors/a/`) and the index file is named `$RBSP_PATH/ECT/Inst.L.sc.dat` which lists all of the downloaded files, their dates, and their versions.

Reading Data

All of the downloaded data can be read directly from the CDF files using `ReadCDF()`.

Some HOPE-specific functions exist:

```
#moment data from HOPE
mom = RBSP.ECT.ReadHOPEMoments(Date,sc)

#spin averaged data
sa = RBSP.ECT.ReadHOPESA(Date,sc)

#Omnidirectional data
omni = RBSP.ECT.ReadHOPEOmni(Date,sc)
```

HOPE Moments

The moments provided by the data repository are warm plasma moments. The functions in this section make an attempt to calculate the cold ion moments.

Prior to calculating the cold ion moments, we need to have downloaded all of the required HOPE Omni data, calculated all of the spacecraft potentials (see EFW), ExB drifts (see VExB), and downloaded all level 4 EMFISIS data (see EMFISIS).

This function calculates all of the moments:

```
mom = RBSP.ECT.CalculateIonMoments(Date,sc,MaxE=0.02)
```

where `MaxE` is the maximum energy bin (keV) to include in the spectral integration (usually around 0.02 keV). The moments are calculated using the method described by Goldstein et al., 2014, Genestreti et al., 2017, and Goldstein et al., 2019.

Moments are all saved to disk (`$RBSP_PATH/Moments/Ions/sc/`, where `sc` is either 'a' or 'b') using `SaveIonMoments()`.

The moments can be read using:

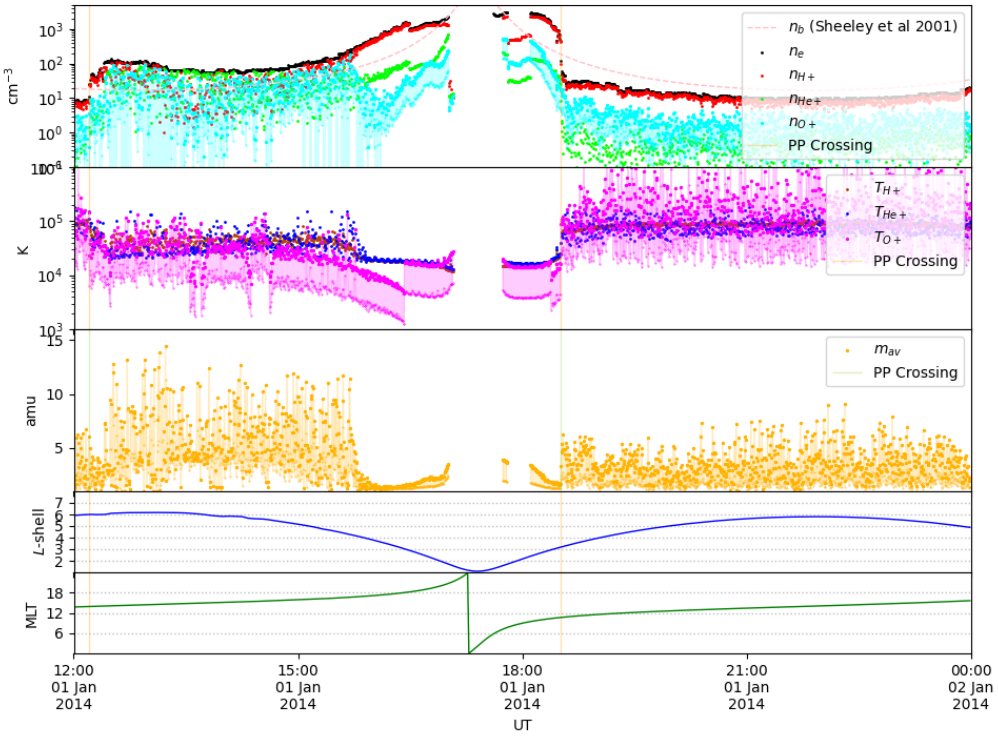
```
mom = RBSP.ECT.ReadIonMoments(Date,sc)
```

Plotting Functions

The ion moments can be plotted using `PlotDensity()`, `PlotTemp()`, and `PlotMav()`, or using `PlotMoments()` which uses all three of the former functions together.

```
# The PlotMoments() function returns a list of axes
axs = RBSP.ECT.PlotMoments(20140101,'a',ut=[12.0,24.0])
```

The above code should produce the plot.



4.2.4 EFW - Electric Field and Waves

The full documentation for this instrument can be found in Wygant et al., 2013.

List of Functions

Function Name	Description
`DownloadData()`	Download latest data files.
`ReadCDF()`	Read a downloaded CDF file.
`DataAvailability()`	Checks what dates have data.
`DeleteDate()`	Deletes data from a specific date.
`RebuildDataIndex()`	Scan the downloaded data and rebuild the index file.
`GetPotential()`	Get the spacecraft potential.
`SavePotentials()`	Save spacecraft potentials for all dates.
`ReadElectronDensity()`	Read the electron density calculated using spacecraft potential.

Downloading Data

The data can be downloaded using different data products, `L`:

`L`	Description
`'l3'`	Spin-fit Electric field in modified-GSE (MGSE) coord, density, and other products
`'l2.spec'`	8 second FFT power spectra
`'l2.e-spinfit-mgse'`	Spin-fit E12 Electric field in MGSE coordinates
`'l2.fbk'`	8 sample/sec filterbank peak, average wave amplitude
`'l2.esvy_despun'`	32 sample/sec despun electric field in MGSE coordinates
`'l2.vsvy-hires'`	16 sample/sec single-ended V1-V6 probe potentials
`'l1.eb1'`	EB1 in UVW coordinates
`'l1.eb2'`	EB2 in UVW coordinates
`'l1.mscb1'`	MSCB1 in UVW coordinates
`'l1.mscb2'`	MSCB2 in UVW coordinates
`'l1.vb1'`	VB1 in UVW coordinates
`'l1.vb2'`	VB2 in UVW coordinates

Spacecraft Potentials

Spacecraft potentials need to be saved first using `SavePotentials()`, e.g.:

```
RBSP.EFW.SavePotentials(sc)
```

where `sc` can be 'a' or 'b'. This will save the potentials for every date found in the 'l3' data.
Read the data using `GetPotential()`, e.g.:

```
data = RBSP.EFW.GetPotential(Date,sc)
```

Electron Density

The electron densities as measured using the spacecraft potential can be obtained using the `ReadElectronDensity()` function, which is a wrapper for the `ReadCDF()` function, e.g.:

```
data = RBSP.EFW.ReadElectronDensity(Date,sc)
```

4.2.5 EMFISIS - Electric and Magnetic Field Instrument Suite and Integrated Science

The details of this instrument can be found in Kletzing et al., 2013.

List of Functions

Function Name	Description
`DownloadData()`	Download latest data files.
`ReadCDF()`	Read a downloaded CDF file.
`DataAvailability()`	Checks what dates have data.
`DeleteDate()`	Deletes data from a specific date.
`RebuildDataIndex()`	Scan the downloaded data and rebuild the index file.
`GetMag()`	Get the magnetometer data.
`ReadElectronDensity()`	Get the UHR electron density.

Downloading Data

The data can be downloaded using different data levels and products, `L` and `Prod`:

L	Prod	Description
'14'	None	densities
'13'	'1sec-***'	1-second resolution magnetic fields
'13'	'4sec-***'	4-second resolution magnetic fields
'13'	'hires-***'	High-resolution magnetic fields
'12'	'HFR-spectra'	
'12'	'HFR-spectra-merged'	
'12'	'HFR-spectra-burst'	
'12'	'HFR-waveform'	
'12'	'WFR-spectral-matrix'	
'12'	'WFR-spectral-matrix-burst'	
'12'	'WFR-spectral-matrix-burst-diagonal'	
'12'	'WFR-spectral-matrix-diagonal-merged'	
'12'	'WFR-spectral-matrix-diagonal'	
'12'	'WFR-waveform'	
'12'	'WFR-waveform-continuous-burst'	

Note that `***` in the above table should be replaced with the coordinate system to be used, e.g., `gsm`, `gse`, etc.

Mag Data

Magnetometer data can be obtained using `GetMag()` once it has been downloaded, e.g.:

```
data = RBSP.EMFISIS.GetMag(Date,sc,ut=[ut0,ut1],Coord='GSE',Res='1sec')
```

where `Date` may be a range or a single date; `ut` will limit the start and end times (in hours); `Coord` can be one of the following strings: 'GSE', 'GSM', 'SM', 'GEO', 'GEI'; and `Res` may be '1sec', '4sec', or 'hires'.

Electron Densities

Electron densities may be read from the 'l4' data using the `ReadElectronDensity()` function, e.g.:

```
data = RBSP.EMFISIS.ReadElectronDensity(Date,sc)
```

4.2.6 Fields

This submodule combines the electric and magnetic fields.

List of Functions

Function Name	Description
`DataAvailability()`	Checks what dates have data.
`CalculateEx()`	Calculates the missing E field component in MGSE.
`CombineFields()`	Combines electric and magnetic field data into one object.
`GetData()`	Get data for more than one date.
`ModelField()`	Uses Tsyganenko field models to obtain model magnetic field vectors.
`ReadData()`	Reads a single data file.

Usage

Get a list of dates where we have field data:

```
dates = RBSP.Fields.DataAvailability(sc)
```

Combine electric and magnetic fields for a single date:

```
RBSP.Fields.CombineFields(20150101,'a')
```

Read combined field for a date:

```
data = RBSP.Fields.ReadData(20140503,'b')
```

Read data between date/time limits of 20140101 12:30 to 20140103 8:15:

```
data = RBSP.Fields.GetData([20140101,20140103],ut=[12.5,8.25],sc='a')
```

4.2.7 Pos

This submodule gets positional data for each spacecraft and can save field traces.

List of Functions

Function	Description
`CalculateVelocity()`	Calculate orbital velocity.
`ConvertH5toBinary()`	Converts the downloaded position data to binary.
`DownloadData()`	Downloads MagEph data.
`GetPos()`	Get all position data for a spacecraft.
`GetVelocity()`	Get all spacecraft velocities.
`PlotL()`	Plot the L-shell.
`PlotMLT()`	Plot magnetic local time.
`ReadFieldTraces()`	Read the field line footprints for a date.
`ReadAllFieldTraces()`	Read all the traces for a spacecraft.
`ReadH5()`	Read the downloaded H5 data directly.
`ReadPos()`	Read converted position binary data.
`SaveFieldTraces()`	Saves the field line footprints.
`TraceFieldDay()`	Performs field tracing for a day.

Usage

Download the position data first:

```
RBSP.Pos.DownloadData(sc='a')
```

Now convert it to binary:

```
RBSP.Pos.ConvertH5toBinary(sc='a')
```

Save the field line traces:

```
RBSP.Pos.SaveFieldTraces(sc='a',Model='T96')
```

Read in position data for the whole mission:

```
posa = RBSP.Pos.GetPos(sc='a')
```

Get the velocity:

```
vela = RBSP.Pos.GetVelocity(sc='a')
```

Get the field trace footprints:

```
fpa = RBSP.Pos.ReadAllFieldTraces(sc='a',Model='T96')
```

4.2.8 RBSPICE - Radiation Belt Storm Probes Ion Composition Experiment

The details of this instrument can be found in Lanzerotti et al., 2013.

List of Functions

Not currently implemented.

4.2.9 RPS - Relativistic Proton Spectrometer

Details for this instrument can be found in Mazur et al., 2013.

List of Functions

Not currently implemented.

4.2.10 VExB

This submodule uses electric and magnetic fields to determine $\mathbf{E} \times \mathbf{B}$ drift, $V_{E \times B}$.

List of Functions

Function	Description
`VExB()`	Calculate drift velocity vector.
`SaveData()`	Save velocity data for a single date.
`ReadData()`	Read the velocity data for a single date.

Usage

Given arrays of electric field components `Ex`, `Ey`, and `Ez`, and magnetic field components `Bx`, `By`, and `Bz`, calculate the velocity vectors:

```
Vx,Vy,Vz = RBSP.VExB(Ex,Ey,Ez,Bx,By,Bz)
```

Save the field vectors for a single date:

```
RBSP.SaveData(20170101,'a')
```

Read those vectors back in from a file:

```
data = RBSP.ReadData(20170101,'a')
```

4.3 cluster: Download and read Cluster data

Download and read in data from the Cluster mission.

4.4 pyCRRES: Download and read CRRES data

Code for the Combined Release and Radiation Effects Satellite (CRRES).

4.5 themissc: Download and read THEMIS data

A python package to download and read THEMIS spacecraft data.

4.6 imageeuv: Download and read IMAGE EUV data

4.7 imagerpi: Download and read IMAGE RPI data

4.8 imagePP: Download and read Goldstein's plasmapause dataset

Simple Python code to download and use Jerry Goldstein's plasmapause database.

4.9 Installation

Clone the project and build:

```
git clone https://github.com/mattkjames7/ImagePP.git
cd ImagePP

#build the wheel file
python3 setup.py bdist_wheel

#install using pip (replace x.x.x with current version)
pip3 install --user dist/ImagePP-x.x.x-py3-none-any.whl
```

The `ImagePP` module requires a directory to download data to. Set the environment variable `$PLASMAPAUSE_DATA` prior to importing the module in Python, either in the terminal or inside `/.bashrc`, e.g.:

```
export PLASMAPAUSE_DATA=/path/to/plasmapauses
```

4.10 Usage

On the first run, the database should be downloaded:

```
import ImagePP as ipp

ipp.Download()
```

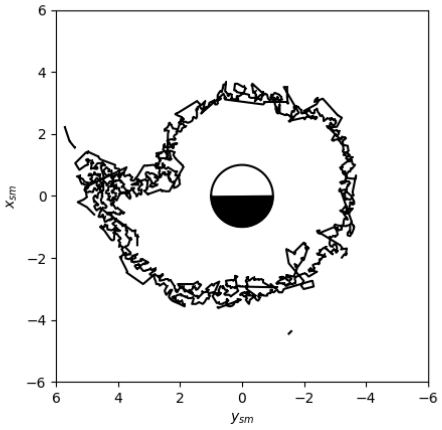
To get a specific plasmapause:

```
#set date in format yyyymmdd
Date = 20010610
ut = 7.0

#get plasmapause coordinates
data = ipp.GetPP(Date,ut)
```

where `data` is a `numpy.recarray` object containing plasmapause coordinates at the equatorial plane in L (`data.L`) and MLT (`data.MLT`) and Cartesian x (`data.x`) and y (`data.y`).

We can also plot that plasmapause (beware, the points are not necessarily stored in order, so results may be wild!):

```
ax = ipp.PlotPP(Date,ut)
```



4.11 PyMess: Download and read MESSENGER data

A Python module for reading the MESSENGER data (or at least some of it)

So far there are some tools for loading and plotting MAG, FIPS and NS data. The spacecraft position can also be retrieved/plotted. A list of bow shock (BS) and magnetopause (MP) crossings based on the work of Winslow et al., 2013 is included, which are used to provide a list of times where MESSENGER is in the solar wind (SW) and the magnetosheath (MSH).

In future I hope to include EPS and XRS submodules too.

4.11.1 Installation

Currently there is no release package on GitHub, nor is there a package to PyPI, so the easiest way to install this module is to download this repository, or clone it using: `git clone https://github.com/mattkjames7/PyMess.git` then to either copy the `PyMess/PyMess` subfolder to your `$PYTHONPATH`, or to create your own Python wheel:

```
cd PyMess
python3 setup.py sdist bdist_wheel
pip3 install dist/PyMess-0.0.1-py3-none-any.whl --user
```

which may, or may not work in the code's current state!

After installation, it would be wise to set up the `$MESSENGER_PATH` environment variable, as this tells the code where to find MESSENGER data.

4.11.2 Submodules

- `FIPS`
- `MAG`
- `NS`
- `Pos`
- `BowShock`
- `Magnetopause`
- `Magnetosheath`
- `ModelField`
- `Tools`

`FIPS` - Fast Imaging Plasma Spectrometer

This module contains routines to read FIPS plasma data. Within the `FIPS` submodule, there is code to convert the PDS (Planetary Data System) data to a more convenient format. The PDS data is stored either in ASCII or binary files. The ASCII files tend to be much larger than necessary, and thus take a long time to read, the binary files are organised in records, which also take a long time to load. The following routines convert both types to a file format where each variable is stored contiguously within the file, allowing for fast reading times and smaller files.

To convert to binary files, run:

```
PyMess.FIPS.PDS.ConvertToBinary()
```

which will scan the `$MESSENGER_PATH/FIPS/PDS` folder for the PDS files.

Another recommended routine combines the new binary files into 1-minute resolution binary files:

```
PyMess.FIPS.Combine60sData()
```

In future, there will be a routine to combine the high time resolution data also.

To load converted data, use the `PyMess.FIPS.ReadFIPS` function, e.g.:

```
data = PyMess.FIPS.ReadFIPS(Date,Type=Type)
```

where `Date` is a 32-bit (or more) integer date in the format yyyymmdd, and `Type` is a string to say the type of data to load, this string can be one of the following:

- 'edr' - To load the EDR data
- 'cdr' - To load the CDR data
- 'ntp' - To load the DDR NTP data
- 'espec' - To load the DDR ESPEC data
- '60' - To load the combined 60s data (default)
- '10' - To load the combined 10s data

`MAG` - Magnetometer

This module contains some basic routines to convert, read and plot the magnetometer data.

To convert PDS data, download PDS data and extract data to `$MESSENGER_PATH/MAG/PDS`. Convert the PDS .TAB files using

```
PyMess.MAG.PDS.ConvertToBinary()
```

which should reduce the size of the dataset from GB to GB.

By default, the magnetometer data used is in MSO coordinates, but we can also rotate the data into a coordinate system more useful for studying ULF waves. In this coordinate system, there is one component parallel to the ambient magnetic field; one oriented in the toroidal/azimuthal direction (eastward); the third component completes the right-handed set and points in the approximately poloidal/radial direction. To convert to these coordinates, run

```
PyMess.MAG.SaveAllRotatedData()
```

To read converted data, for MSO data:

```
data = PyMess.MAG.ReadMagData(Date)
```

For rotated data:

```
data = PyMess.MAG.ReadRotatedData(Date)
```

Also, for magnetopause normal data (based on the magnetopause used by the KT17 magnetic field model):

```
data = PyMess.MAG.MagDataMPN(Date)
```

To plot data:

```
PyMess.MAG.PlotMagData(Date,ut=ut,MagType=MagType)
```

Where, `Date` is a one or two element integer, with the format yyyymmdd, `ut` is a two element list, array or tuple, denoting the time range (from 0 - 24) and `MagType` is a string equal to one of the following: `'MSM'`—`'Rotated'`—`'MPN'`.

All of the aforementioned routines have a range of keywords which can be found in their docstrings.

NS - Neutron Spectrometer

This submodule contains some basic routines to convert the NS PDS data to a better binary format, and also to read the new data.

To convert PDS data, place PDS files in `$MESSENGER_PATH/NS/PDS`, where the code will look for them, then run:

```
PyMess.NS.PDS.ConvertToBinary()
```

To read converted data:

4.12 FIPSProtonData: Download and read ANN verified FIPS moments

This Python package was written to provide a simple mechanism for reading and plotting the plasma moments calculated for the MESSENGER FIPS proton spectra.

The moments were found by numerically fitting the kappa distribution function to each proton spectrum using the downhill-simplex method. The quality of each fit was then assessed using neural networks, which classified each spectrum as either "good" or "bad".

WARNING: This is not yet published - do not use for anything serious yet!

4.12.1 Requirements

The following requirements should be installed automatically when using `pip3` to install the package:

- Python 3
- numpy
- matplotlib
- DateTimeTools
- scipy

4.12.2 Installation

For Linux and possibly Mac:

1. Download the latest released wheel here.
2. Open terminal in folder where the wheel was downloaded to.
3. Use `pip3` to install the wheel, e.g.

   ```
   pip3 install FIPSProtonData-0.0.1-py3-none-any.whl --user
   ```

   where the `--user` flag will install the package locally. Replace the file name above with the name of the downloaded wheel.

Windows:

1. In cmd type `format C:`
2. Install Linux.

4.12.3 Usage

First run

Ideally you would set up an environment variable called `MESSENGER_PATH` which points to a writable directory where you store MESSENGER data, e.g.

```
export MESSENGER_PATH=/data/path/to/MESSENGER
```

This can be done in your .bashrc file, or just run it before starting `python3` or `ipython3`.

To start using the module, open `python3` or `ipython3` and run:

```
import FIPSProtonData as fpd
```

As the module is imported, it will try to find the `MESSENGER_PATH` if it is set, if not it will use the current working directory.

Loading data

To read in the data simply type in something to the effect of the following:

```
data = fpd.GetData()
```

The first time the `GetData` function is called, it will search the current `MESSENGER_PATH` for the data file, then download it when it finds that the file doesn't exist. The data will be downloaded to a subdirectory, `$MESSENGER_PATH/FIPS/`.

The `data` object is a `numpy.recarray` object, containing the following fields:

Fields	dtype	Description
Date	int32	Date in format yyyymmdd
ut	float32	UT in format hh.hhhhh...
mlatn	float32	Magnetic latitude of MESSENGER traced to the north
mlats	float32	Magnetic latitude of MESSENGER traced to the south
latn	float32	Latitude of MESSENGER traced to the north
lats	float32	Latitude of MESSENGER traced to the south
mltn	float32	Magnetic local time of MESSENGER traced to the north
mlts	float32	Magnetic local time of MESSENGER traced to the south
lctn	float32	Local time of MESSENGER traced to the north
lcts	float32	Local time of MESSENGER traced to the south
mlte	float32	MLT of equatorial trace footprint
lshell	float32	L-shell of equatorial footprint
fl_len	float32	Field line length in Rm
x	float32	X-msm coordinate or MESSENGER in Rm
y	float32	Y-msm coordinate or MESSENGER in Rm
z	float32	Z-msm coordinate or MESSENGER in Rm
Loc	U2	String of 'MS','MP','SH','BS','SW','UK'
n	float32	Density in cm^{-3}
t	float32	Temperature in MK
K	float32	Kappa parameter
Bx	float32	X component of local magnetic field
By	float32	Y component of local magnetic field
Bz	float32	Z component of local magnetic field
Rsm	float32	Radial distance of subsolar magnetopause in Rm
Rau	float32	Radial distance of Mercury from the Sun in AU
Class	int8	Indicator of good (==1) or bad (==0) spectrum

The fields in `data` are easy to access, e.g.:

```
x = data[i].lshell # single element access
x = data.lshell[i] # single element access, equivalent to above
x = data.lshell # array access, x becomes a numpy.ndarray
```

The field line traces which provide the field line length, equatorial footprint, and planetary footprint information were traced using the KT17 magnetic field model (Korth et al., 2015; Korth et al., 2017), the code for which can be found in https://github.com/mattkjames7/KT17.

The `Loc` variable corresponds to the location of MESSENGER in Mercury's plasma environment at the time of the FIPS measurement. These locations were found using the method described in Winslow et al., 2013.

Plotting data

There are two plotting routines which come with this module: `fpd.PlotParameter` and `fpd.QuickPlot`.

`QuickPlot` will plot *n*, *T*, κ, B_x, B_y, B_z, and $\pm|\mathbf{B}|$ on a single page using:

```
fpd.QuickPlot(Date,ut,ShowClass=True)
```

where `Date` is either a single integer or a two-element list, tuple, or array of integers in the format *yyyymmdd*, e.g., 12th June 2014 is formatted 20120612. `ut` is a two-element list, tuple, or array of floating-point values, where the time is formatted in hours, so a time of 13:45:00 would be written as 13.75 (i.e. hh + mm/60 +

ss/3600). `ShowClass` is a Boolean value and shows whether each spectral fit was considered to be good or bad by shading the background either green or red, respectively.

`PlotParameter` is used to plot a single parameter, where one may choose from 'n', 'T', 'K', 'Bx', 'By', 'Bz', 'B', or 'Class', e.g.:

```
fpd.PlotParameter('n',Date,ut)
```

`Date` and `ut` are the same format as for `QuickPlot`, all other keyword arguments can be found in the docstring by typing:

```
fpd.PlotParameter?
```

4.13 VenusExpress: Download and read VEX data

Chapter 5

Ground Data and Geomagnetic Indices

5.1 groundmag: Tools for processing and reading ground magnetometer data

5.2 SuperDARN: Simple SuperDARN fitacf reading code

https://github.com/mattkjames7/SuperDARN

The `SuperDARN` module is for reading and plotting SuperDARN fitacf files. It is a fairly simple tool, but use with caution because there may be some errors...

5.2.1 Installation

This package is not in the PyPI, so manual installation is necessary:

```
#clone the repo
git clone https://github.com/mattkjames7/SuperDARN
cd SuperDARN

#build a Python package
python3 setup.py bdist_wheel

#install it (replace 0.1.0 with whatever version is built)
pip3 install dist/SuperDARN-0.1.0-py3-none-any.whl --user
```

Once installed, the directory used to create the Python wheel file can be deleted. It can be uninstalled using `pip3 uninstall SuperDARN`.

Before running for the first time, a couple of environment variables need to be set up to tell the module where to look for fitacf files and to say where it is able to store some files:

```
#path to where FITACF files are stored
#(this one is specific to SPECTRE)
export FITACF_PATH=/data/sol-ionosphere/fitacf

#path to where this module can create some files
#(this should be a path where you have write access)
export SUPERDARN_PATH=/some/other/path/SuperDARN
```

This module will not currently run on Windows (as far as I am aware) because it requires the compilation of some C++ code which is not yet cross-platform.

Usage

In ipython, the first time this module is imported, it should attempt to download some files from the Radar Software Toolkit (RST) which help in calculating the coordinates of the fields of view of each radar. These files are created in the path defined be the `$SUPERDARN_PATH` variable.

Reading Data

There are a few functions within `SuperDARN.Data` which provide objects containing data:

```
import SuperDARN as sd

#get the data from a single cell (Radar,Date,ut,Beam,Gate)
cdata = sd.Data.GetCellData('han',20020321,[22.0,24.0],9,25)

#or a whole beam of data (Radar,Date,ut,Beam)
bdata = sd.Data.GetBeamData('han',[20020321,20020322],[22.0,24.0],7)

#data for the whole field of view (Radar,Date,ut)
#in this case, the output is a dict where each key is a beam number
#pointing to a recarray for each beam as produced by GetBeamData
rdata = sd.Data.GetRadarData('han',[20020321,20020322],[22.0,23.0])
```

In the above examples `bdata` and `cdata` are `numpy.recarray` objects, `rdata` is a `dict` object containing a `numpy.recarray` for each beam.

The fitacf data are stored in memory once loaded so that they don't need to be re-read every time the data are requested. To check how much memory is in use and to clear it:

```
#check memory usage in MB
sd.Data.MemUsage()

#clear memory
sd.Data.ClearData()
```

Plotting Data

There are a bunch of very simple plotting functions, e.g.:

```
import matplotlib.pyplot as plt

#create a figure
plt.figure(figsize=(8,11))

#plot the power along a beam
ax0 = sd.Plot.RTIBeam('han',[20020321,20020322],[23.0,1.0],9,[20,35],
                                        Param='P_l',ShowScatter=True,fig=plt,
                                        maps=[2,3,0,0],scale=[1.0,100.0],zlog=True,
                                        cmap='gnuplot')

#the velocity
ax1 = sd.Plot.RTIBeam('han',[20020321,20020322],[23.0,1.0],9,[20,35],Param='V',
                                        fig=plt,maps=[2,3,1,0])

#velocity along a range of latitudes at a ~constant longitude of 105
ax2 = sd.Plot.RTILat('han',[20020321,20020322],[23.0,1.0],105.0,Param='V',
                                        fig=plt,maps=[2,3,0,1])

#velocity along a range of longitudes at a ~constant latitude of ~70
ax3 = sd.Plot.RTILon('han',[20020321,20020322],[23.0,1.0],70.0,Param='V',
                                        fig=plt,maps=[2,3,1,1])

#some specific cells
beams = [1,5,7,2,8,4,9]
gates = [20,26,33,22,25,21,29]
ax4 = sd.Plot.RTI('han',[20020321,20020322],[23.0,1.0],beams,gates,
                                        Param='V',fig=plt,maps=[2,3,0,2])

#totally different FOV plot
```

```
ax5 = sd.Plot.FOVData('han',20020321,23.5,Param='V',fig=plt,maps=[2,3,1,2])


plt.tight_layout()
```

which should produce figure 5.1.

Fields of View

These may be wrong. Use with great caution.

The fields of view of each radar are stored as instances of the `SuperDARN.FOV.FOVObj` objects in memory and can be accessed using `GetFOV`, e.g.:

```
#get the object from memory
Date = 20020321
fov = sd.FOV.GetFOV('pyk',Date)

#use it to retrieve the FOV in mag coordinates
mlon,mlat = fov.GetFOV(Mag=True,Date=Date)

#plot it
ax = fov.PlotPolar(Background=[0.0,0.2,1.0],Continents=[0.0,1.0,0.2],
                                color='magenta',ShowBeams=False,ShowCells=False,
                                linewidth=2.0,Mag=True,Lon=True)

#add some cells
beams = [1,5,7,2,8,4,9]
gates = [20,26,33,22,25,21,29]
fov.PlotPolarCells(beams,gates,color='red',fig=ax,Mag=True,linewidth=2.0,Lon=True)
```

The above code should look like figure 5.2:

5.3 kpindex: Download the latext Kp indices

Very simple package for obtaining the planetary Kp index data (see https://www.gfz-potsdam.de/en/kp-index/ for more information)

5.3.1 Installation

This package depends on the following:

- numpy
- RecarrayTools
- PyFileIO

which are all available on PyPI.

Installation is simple and can be done in one of four ways:

Method 1

This method simply uses the Python `pip3` command to download this module and its dependencies:

```
pip3 install kpindex --user
```

Method 2

This method uses the Python wheel on the "releases" page of this repository. Download the wheel, then install using `pip3`:

```
pip3 install kpindex-0.0.1-py3-none-any.whl --user
```

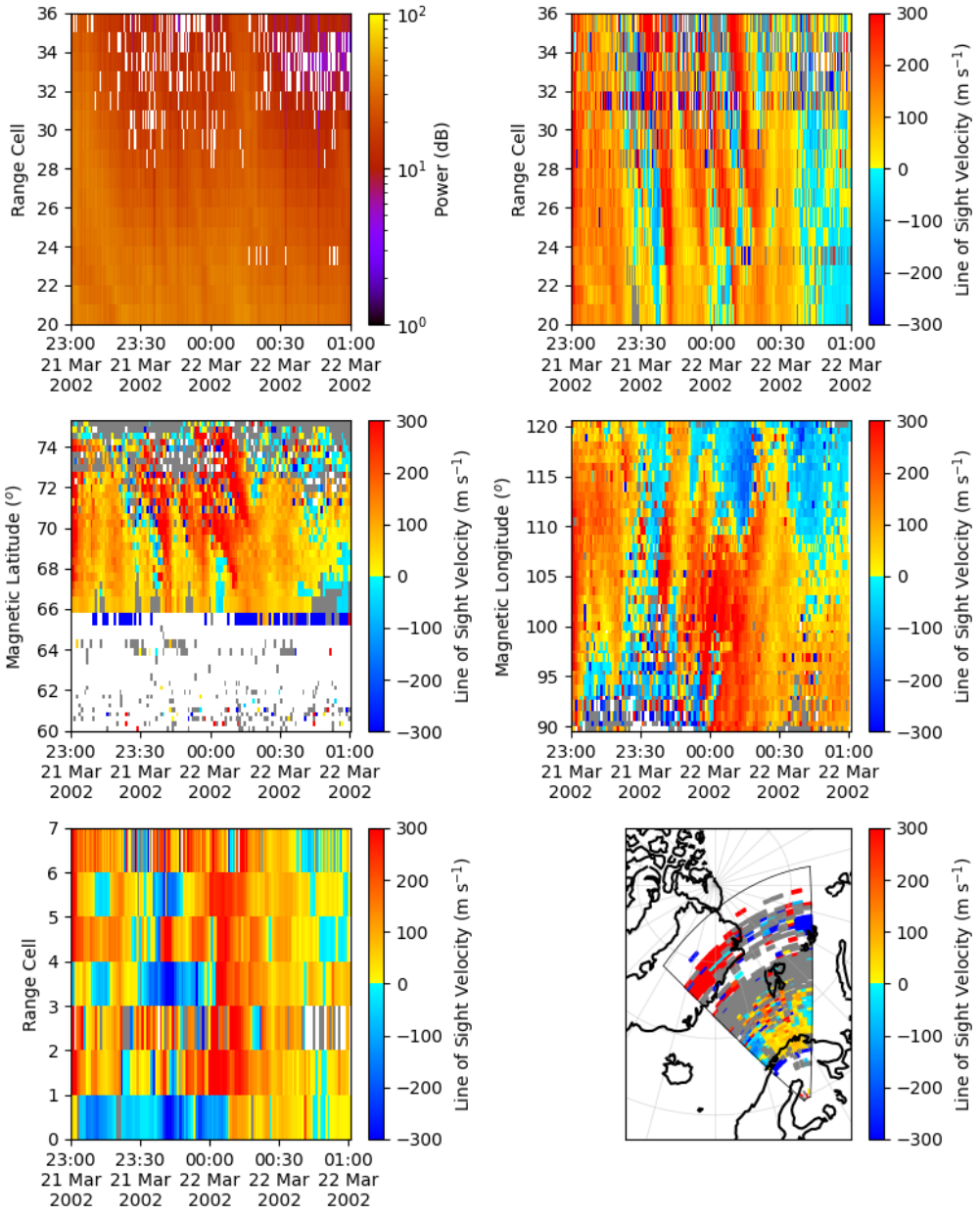


Figure 5.1: Top left: range time intensity (RTI) plot of backscatter power. Top right: RTI plot of line of sight velocity. Mid left: velocity along a line of cells in magnetic longitude. Mid right: velocity along a range of longitudes. Bottom left: velocity of specific range cells. Bottom right: velocity within the field of view plot.

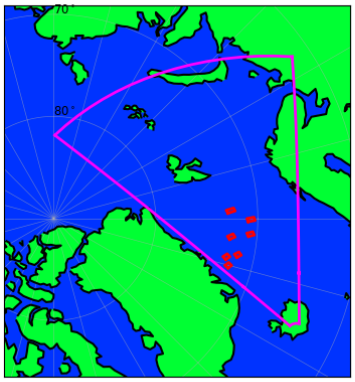


Figure 5.2: SuperDARN field of view plot with specific cells highlighted.

Method 3

Don't trust my prepackaged stuff? OK, clone this repository and build your own:

```
git clone https://github.com/mattkjames7/kpindex.git
cd kpindex
python3 setup.py bdist_wheel
pip3 install dist/kpindex-0.0.1-py3-none-any.whl --user
```

Method 4

So you don't like wheels? Fine. Clone the repository and just move the "kpindex" folder to your `$PYTHONPATH`.

5.3.2 Post-Install

In order for the module to be able to download the Kp index data from the FTP site, you will need to point it in the direction of a directory where you have read and write access using the `$KPDATA_PATH` environment variable. This can be done either by running the following in the terminal before starting Python, or inserting it into your `~/.bashrc` file:

```
export KPDATA_PATH=/path/to/the/data
```

5.3.3 Usage

Using this module is very simple: the first time you run it you will need to update the database (also when you think the database is out of date) e.g.

```
import kpindex
kpindex.UpdateLocalData()
```

It may take a couple of minutes to download the data and convert it, then you are ready to read the data:

```
data = kpindex.GetKp(Date)
```

where `Date` could be `None`, in which case ALL of the Kp indices ever will be returned; `Date` could be a single date in the format yyyymmdd, in which case only Kp indices from that date will be returned; finally, it could be a two-element array/list/tuple containing two dates, in this case, it will return all the indices from the start to the end date.

Enjoy!

5.4 pyomnidata: Download the latext OMNI and solar flux data

Python tool for downloading, converting, and reading OMNI solar wind data.

If you make use of the OMNI data please acknowledge and cite as specified here: https://omniweb.gsfc.nasa.gov/html/citing.html

5.4.1 Installation

Simply install using `pip3`:

```
pip3 install pyomnidata --user
```

Alternatively install from this repository:

```
git clone https://github.com/mattkjames7/pyomnidata
cd pyomnidata

#EITHER build a wheel and install with pip (better)
python3 setup.py bdist_wheel
pip3 install dist/pyomnidata-1.0.0-py3-none-any.whl --user

#OR directly using setup py (should work, not tested though)
python3 setup.py install --user
```

For this to work properly - you will need to set up the `$OMNIDATA_PATH` environment variable to point to a folder where you want to store the data. Do this by adding something along the lines of the following to the bottom of your `~/.bashrc` file:

```
export OMNIDATA_PATH=/path/to/omni/data
```

5.4.2 Usage

Downloading Data

Download OMNI data like this:

```
import pyomnidata

#download all available data
pyomnidata.UpdateLocalData()
```

Download F10.7 index (solar flux at 10.7 cm):

```
pyomnidata.UpdateSolarFlux(EndDate=2021024)
```

where `EndDate` is the last date for which you want to request solar flux data. This should be set to a date at least a few days prior to the current date. If you request a date that currently has no available data, the download will fail.

Read Data

Get the OMNI parameters like so:

```
####OMNI parameters####
#Year can either be a single year:
Year = 2001
#or it can be a range:
Year = [2001,2004]

#5 minute resolution data
data = pyomnidata.GetOMNI(Year,Res=5)

#1 minute data
data = pyomnidata.GetOMNI(Year,Res=1)

####solar flux###
#all of the data
data = pyomnidata.GetSolarFlux()

#a single date
```

```
data = pyomnidata.GetSolarFlux(Date=20050101)

#a range of dates
data = pyomnidata.GetSolarFlux(Date=[20020101,20020103])
```

The returned `data` object is a `numpy.recarray` object which contains all of the OMNI data requested. To see what fields are stored use `print(data.dtype.names)`. The units are as presented here: https://omniweb.gsfc.nasa.gov/html/omni_min_data.html#4b

Plot Data

Use the `PlotOMNI` function, e.g.:

```
import matplotlib.pyplot as plt

#create a figure
plt.figure(figsize=(11,6))

#plot some stuff in one panel
ax0 = pyomnidata.PlotOMNI(['SymH','SymD'],[20010101,20010120],fig=plt,maps=[2,1,0,0])

#and a second panel
ax1 = pyomnidata.PlotOMNI(['FlowSpeed'],[20010101,20010120],fig=plt,maps=[2,1,1,0])

#fit things a bit nicer
plt.tight_layout()
```

Which should produce something like the following:

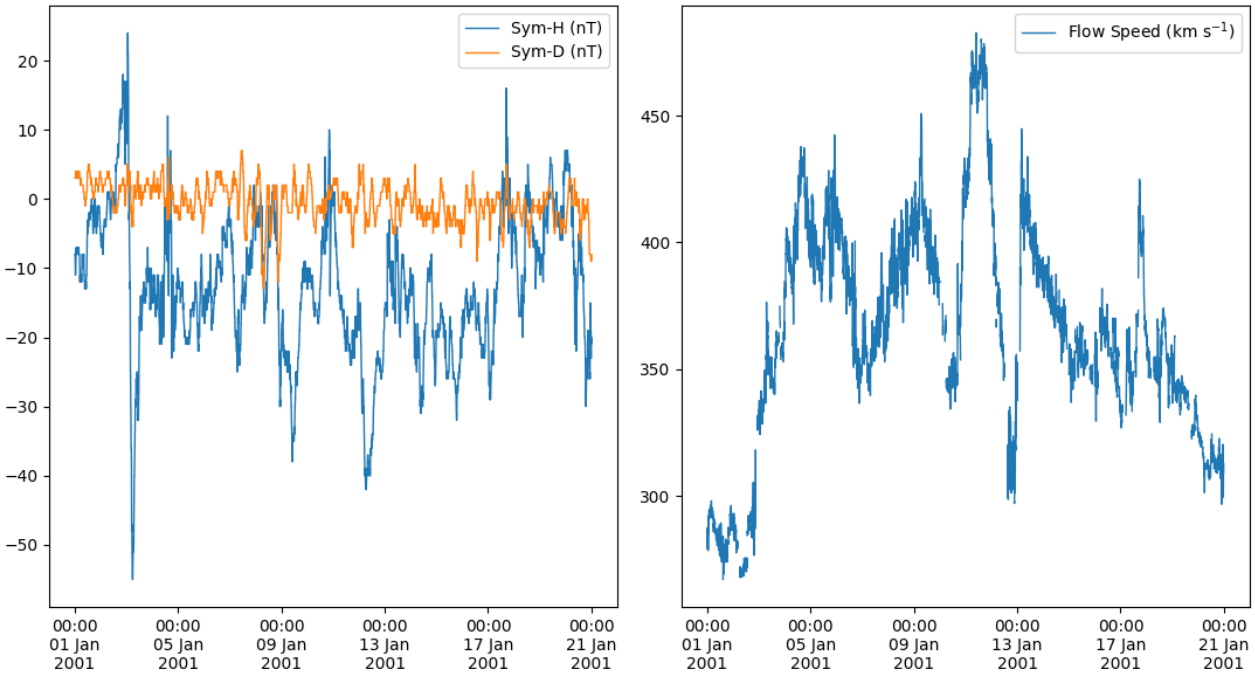


Figure 5.3: Example plot using `pyomnidata`.

5.5 smindex: Read the SuperMAG indices

A tiny module for reading SuperMAG indices and substorm lists.

For the SuperMAG data visit https://supermag.jhuapl.edu/indices

If using any of these data products, please remember to cite the relevant SuperMAG papers and acknowledge SuperMAG (see here: https://supermag.jhuapl.edu/info/?page=rulesoftheroad)

5.5.1 Installation

Install this module using `pip3`:

```
pip3 install smindex --user
```

Or by cloning and building this repository:

```
git clone https://github.com/mattkjames7/smindex
cd smindex
python3 setup.py bdist_wheel
pip3 install dist/smindex-1.0.0-py3-none-any.whl --user
```

Then set up an environment variable which points to where you want to store the data in your `~/.bashrc` file:

```
export SMINDEX_PATH=/path/to/smindex/data/
```

5.5.2 Downloading Indices

For best results, visit the indices page on the SuperMAG website and select the following indices to download:
SME U/L, SME, SME MLT, SME MLAT, SME LT, SMU LT, SML LT, SMR, SMR LT
(follow this link: https://supermag.jhuapl.edu/indices/?layers=SMR.LT,SMR,SMER.L,SMER.U,SMER.E,SME.MLAT,SME.MLT,SME.E,SME.UL&fidelity=low&start=2001-01-30T00%3A00%3A00.000Z&step=14400&tab=download)
The data format should be ASCII and ideally download full-year files.
These data files should then be placed in the directory $SMINDEX_PATH/downloadwheretheycanbeprocessed.
They can be converted to a binary format which is quick to read:

```
import smindex
smindex.ConvertData()
```

5.5.3 Read Indices

Use the smindex.GetIndices function to read the converted index files:

```
#Read a single year file
data = smindex.GetData(2005)

#or a range of years
data = smindex.GetData([2005,2008])
```

5.5.4 Downloading Substorm Lists

Substorm lists (by Frey et al., 2004 and 2006; Liou 2010; Newell and Gjerloev, 2011; Forsyth et al., 2015; Ohtani and Gjerloev, 2020) can be downloaded from the following page: https://supermag.jhuapl.edu/substorms/?tab=download
The ASCII file format is readable by this module. The files should be placed in $SMINDEX_PATH/subst
Once you have all of the data files, they can be combined using the following function:

```
smindex.UpdateSubstorms()
```

5.5.5 Reading Substorms

The best way to read the substorm lists is to use the GetSubstorms function:

```
#get everything:
ss = smindex.GetSubstorms()

#get a single date (25th January 2005 in this case)
ss = smindex.GetSubstorms(Date=20050125)

#get a range of dates
ss = smindex.GetSubstorms(Date=[20050101,20050125])
```

Chapter 6

Machine Learning

6.1 NNClass: Simple neural network classifier module

A simple bit of code for training classification neural networks.

6.1.1 Installation

Install from pip3:

```
pip3 install --user NNClass
```

Or by cloning this repository:

```
#clone the repo
git clone https://github.com/mattkjames7/NNClass
cd NNClass

#Either create a wheel and use pip: (X.X.X should be replaced with the current version)
python3 setup.py bdist_wheel
pip3 install --user dists/NNClass-X.X.X-py3-none-any.whl

#Or by using setup.py directly
python3 setup.py install --user
```

6.1.2 Usage

Start by training a network:

```
import NNClass as nnc

#create the network, defining the activation functions and the number of nodes in each layer
net = nnc.NNClass(s,AF='sigmoid',Output='softmax')

#note that s should be a list, where each element denotes the number of nodes in each layer

#input training data
net.AddData(X,y)
#Input matrix X should be of the shape (m,n) - where m is the number of samples and n is the nu
#Output hypothesis matrix y should either be
# an array (m,) of integers corresponding to class
# or matrix (m,k) of one-hot labels

#optionally add validation and test data
net.AddValidationData(Xv,yv)
#Note that validation data is ignored if kfolds > 1 during training
net.AddTestData(Xt,yt)

#Train the network
```

```
net.Train(nEpoch,kfolds=k)
#nEpoch is the number of training epochs
#kfolds is the number of kfolds to do - if kfolds > 1 then the training data are split
#into kfold sets, each of which has a turn at being the validation set. This results in
#kfold networks being trained in total (net.model)
#see docstring net.Train? to see more options
```

After training, the cost function may be plotted:

```
net.PlotCost(k=k)
```

We can use the network on other data:

```
#X in this case is a new matrix
y = net.Predict(X)
```

The networks can be saved and reloaded:

```
#save
net.Save(fname='networkname.bin')

#reload
net = nnc.LoadANN(fname='networkname.bin')
```

Running mnist = nnc.Test() will perform a test on the code, by training a neural network to classify a set of hand-written digits (0-9) from the MNIST dataset (https://deepai.org/dataset/mnist). The function will then plot out the cost, accuracy and an example of a classified digit, e.g.:

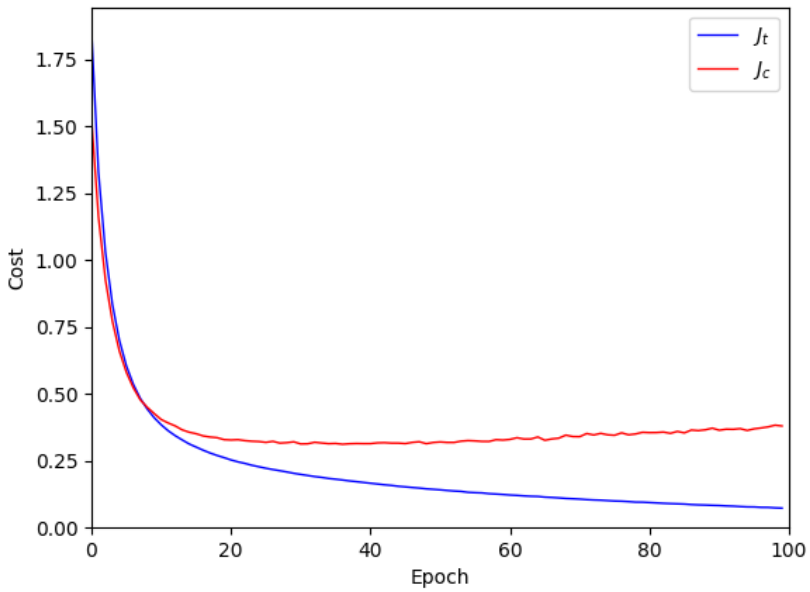


Figure 6.1: Cost plot

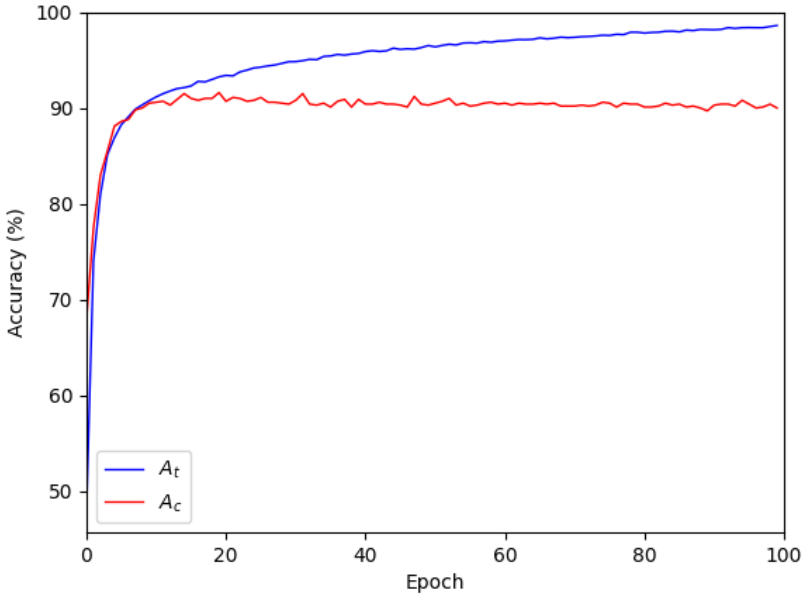


Figure 6.2: Accuracy plot

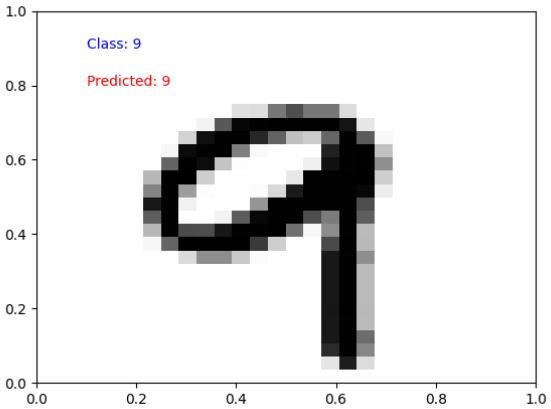


Figure 6.3: Example of a classified digit

The 10,000 sample MNIST data can be accessed using the NNClass.MNIST object.

6.2 NNFunction: Train neural networks on arbitrary functions

A simple package for modelling multidimensional non-linear functions using artificial neural networks.

6.2.1 Installation

Install from pip3:

```
pip3 install --user NNFunction
```

Or by cloning this repository:

```
#clone the repo
git clone https://github.com/mattkjames7/NNFunction
cd NNFunction
```

```
#Either create a wheel and use pip: (X.X.X should be replaced with the current version)
python3 setup.py bdist_wheel
pip3 install --user dists/NNFunction-X.X.X-py3-none-any.whl

#Or by using setup.py directly
python3 setup.py install --user
```

6.2.2 Usage

Start by training a network:

```
import NNFunction as nnf

#create the network, defining the activation functions and the number of nodes in each layer
net = nnf.NNFunction(s,AF='softplus',Output='linear')

#note that s should be a list, where each element denotes the number of nodes in each layer

#input training data
net.AddData(X,y)
#Input matrix X should be of the shape (m,n) - where m is the number of samples and n is the nu
#Output hypothesis matrix y should have the shape (m,k) - where k is the number of output nodes

#optionally add validation and test data
net.AddValidationData(Xv,yv)
#Note that validation data is ignored if kfolds > 1 during training
net.AddTestData(Xt,yt)

#Train the network
net.Train(nEpoch,kfolds=k)
#nEpoch is the number of training epochs
#kfolds is the number of kfolds to do - if kfolds > 1 then the training data are split
#into kfold sets, each of which has a turn at being the validation set. This results in
#kfold networks being trained in total (net.model)
#see docstring net.Train? to see more options
```

After training, the cost function may be plotted:

```
net.PlotCost(k=k)
```

We can use the network on other data:

```
#X in this case is a new matrix
y = net.Predict(X)
```

The networks can be saved and reloaded:

```
#save
net.Save(fname='networkname.bin')

#reload
net = nnf.LoadANN(fname='networkname.bin')
```

The animation below demonstrates the training of a neural network used to reproduce four different functions simultaneously. It was produced using NNFunction.TrainNN4.

Chapter 7

Other Tools

7.1 wavespec: Spectral analysis tools

Some spectral analysis tools for analyzing waves in data.

7.1.1 Installation

Using pip3:

```
pip3 install wavespec --user
```

Installing the wheel using pip3:

```
pip3 install wavespec-0.0.1-py3-none-any.whl --user
```

From git:

```
git clone https://github.com/mattkjames7/wavespec
cd wavespec
python3 setup.py install --user
```

7.1.2 Usage

```
import wavespec as ws
```

Fast Fourier Transform (FFT)

```
power,phase,freq,fr,fi = ws.Fourier.FFT(t,x,WindowFunction=None,Param=None)
```

Lomb-Scargle (LS)

```
P,A,phi,a,b = ws.LombScargle.LombScargle(t,x0,f,Backend='C++',WindowFunction=None,Param=None)
```

Spectrograms

```
Nw,LenW,Freq,out = ws.Spectrogram.Spectrogram(t,v,wind,slip,Freq=None,Method='FFT',WindowFuncti

ax,Nw,LenW,Freq,Spec = ws.Spectrogram.PlotSpectrogram(t,v,wind,slip,Freq=None,Method='FFT',Wind
```

3D Spectrograms

```
Nw,LenW,Freq,Spec = ws.Spectrogram.Spectrogram3D(t,vx,vy,vz,wind,slip,Freq=None,Method='FFT',Wi
```

Tests

```
ws.Test.TestLS(A=[1.0,2.0],f=[0.04,0.1],phi=[0.0,90.0],Backend='C++')
ws.Test.TestPolarization(xPow=2.0,xPhase=0.0,yPow=1.0,yPhase=40.0)
ws.Test.TestSpectrogram()
```

7.2 MHDWaveHarmonics: Tools for MHD waves

Some simple tools for modelling MHD wave harmonics in an arbitrary magnetic field geometry.

7.2.1 Installation

Install using pip3:

```
pip3 install MHDWaveHarmonics --user
```

The installation will require the following packages:

- numpy
- scipy
- matplotlib
- PyGeopack
- FieldTracing

all of which will be installed automatically. For modelling waves in Mercury's magnetosphere, you will also require the KT17 model.

7.2.2 Usage

1. GetFieldLine

The GetFieldLine function will trace a model field, returning a TraceField object alongside a numpy.ndarray, s, which contains the distance along the traced field line and optionally h if the polarization is specified:

```
import MHDWaveHarmonics as wh
T,s = wh.GetFieldLine(pos,Date=None,ut=None,Model='KT17',Delta=None,Polarization='none',**kwarg
T,s,h = wh.GetFieldLine(pos,Date=None,ut=None,Model='KT17',Delta=None,Polarization='poloidal',*
```

where h is provided using a second trace if the Polarization parameter is set to 'poloidal', 'toroidal', or a float corresponding to an angle in degrees anticlockwise from the poloidal direction (the outward pointing normal direction of the field line). Use wh.GetFieldLine? to find out more about this procedure from its docstring.

2. SolveWave

This procedure will attempt to solve the wave equation along an arbitrary magnetic field trace such as that provided by GetFieldLine:

```
yr = wh.SolveWave(f,x,B,R=None,Va=None,halpha=None,Params=None,InPlanet=None,Method='Simple',Un
yr,yi,phase = SolveWave(f,x,B,R=None,Va=None,halpha=None,Params=None,InPlanet=None,Method='Comp
```

where yr is the real part of the scaled field displacement, ξ/h_α, yi is the imaginary part, and phase is a continuous measure of the waves phase along the trace. See the docstring for more information.

3. FindHarmonics

This will attempt to solve the wave equation to find a number of harmonics that would be allowed to exist:

```
freq,success,niter = wh.FindHarmonics(T,s,Params,halpha=None,Harmonics=[1,2,3],x0=None,df=1.0,M
```

where freq is an array of allowed frequencies, success is a Boolean array denoting whether each fit was successful or not, and niter is an array containing the number of iterations required for each fit.

4. CalcFieldLineVa

This will calculate the Alfven speed at each point along the trace:

```
va = CalcFieldLineVa(T,s,Params,halpha=None)
```

or at the midpoint between each pair of consecutive steps along the trace:

```
vamid = CalcFieldLineVaMid(T,s,Params,halpha=None)
```

5. PlotHarmonics

This will produce a plot of the allowed toroidal and poloidal harmonics on a field line given an initial position for the trace and a plasma mass density profile along the field.

```
PlotHarmonics(pos,Params,nh=3,df=1.0,Rp=1.0,Colours=None,Method='Complex',**kwargs)
```

6. FitPlasmaToHarmonic

Attempts to fit a power law or the Sandhu et al model plasma mass density profile to a given field trace.

```
p_eq = FitPlasmaToHarmonic(T,s,halpha,f,Params,Harm=1,df=1.0,Method='Complex')
```

7. FitPlasma

This tries to fit the plasma mass density profile to a set of observed frequencies (with their assumed harmonic numbers) along a field trace.

```
params = FitPlasma(T,s,halpha,freqs,harms,Params0,df=1.0,Method='Complex',ParamFit=None)
```

8. GetSandhuParams

Calculates the parameters for the Sandhu et al electron density and average ion mass models.

```
ne0,alpha,a,beta,mav0 = GetSandhuParams(mlt,L)
```

9. PlotFieldLineDensity

Plots the modelled density along a field line given a position in which to start a field trace and a set of plasma profile parameters.

```
PlotFieldLineDensity(pos,Params,fig=None,maps=[1,1,0,0],Overplot=False,**kwargs)
```

7.3 FieldTracing: Python field tracing code

This is a very simple Python module to trace fields (e.g., magnetic fields) when provided with a model.

7.3.1 Installation

Install using pip3:

```
pip3 install --user FieldTracing
```

Or by cloning this repo:

```
#clone the repo
git clone https://github.com/mattkjames7/FieldTracing
cd FieldTracing

#Either create a wheel and use pip: (X.X.X should be replaced with the current version)
python3 setup.py bdist_wheel
pip3 install --user dists/FieldTracing-X.X.X-py3-none-any.whl

#Or by using setup.py directly
python3 setup.py install --user
```

7.3.2 Usage

There are two tracing routines in this model: FieldTracing.Euler.EulerTrace - this is the most basic tracing routine, which will step in the direction of the field using the Euler method; FieldTraci - this uses the 4th order Runge-Kutta method. If you are tracing any non-linear field, the RK4 method would most likely be the better choice.

For more information about keywords and arguments supplied to each function:

```
import FieldTracing as ft

ft.RK4.RK4Trace?
ft.Euler.EulerTrace?
```

Below is an example trace using the KT17 model field module (see https://github.com/mattkjames7/KT17):

```
import KT17
import FieldTracing as ft
import matplotlib.pyplot as plt

#define a model field function which will accept a vector position and return a field vector
def modelfunc(p):
	#accepts position with shape (3,)
	B = KT17.ModelField(p[0],p[1],p[2])
	#return field with shape (3,)
	return np.array(B).flatten()

#define a function which says whether we are within some acceptable tracing bounds
def boundsfunc(p):
	#check if we are within the planet (note that Mercury has a vertical dipole offset)
	r = np.sqrt(p[0]**2 + p[1]**2 + (p[2]+0.196)**2)
	#we want this to terminate at the surface of the iron core, so we should return True as
	return r > 0.83

#call the field tracing function, from some initial position
x0 = [1.2,0.0,0.0]
Tr = ft.RK4.RK4Trace(x0,0.02,modelfunc,bounds=boundsfunc)
Te = ft.Euler.EulerTrace(x0,0.02,modelfunc,bounds=boundsfunc)

#call the built-in KT17 trace
T = KT17.TraceField(*x0,LimType=17)

#plot to compare
a = np.arange(361)*np.pi/180.0
x = np.cos(a)
z = np.sin(a) - 0.196
xc = 0.83*np.cos(a)
zc = 0.83*np.sin(a) - 0.196
plt.figure()
ax = plt.subplot2grid((1,1),(0,0))
ax.plot(x,z,color=[0.0,0.0,0.0,0.7],label='Mercury Surface',lw=4)
ax.plot(xc,zc,color=[0.5,0.5,0.5,0.7],label='Mercury Core',linestyle='--',lw=4)
ax.plot(Tr[:,0],Tr[:,2],color='red',label='FieldTrace (RK4)')
ax.plot(Te[:,0],Te[:,2],color='lime',label='FieldTrace (Euler)')
ax.plot(T.x,T.z,color='blue',label='KT17.TraceField',linestyle=':')
ax.set_xlabel('$x_{MSM}$')
ax.set_ylabel('$z_{MSM}$')
ax.set_aspect(1.0)
ax.legend()
```

Which should produce this:

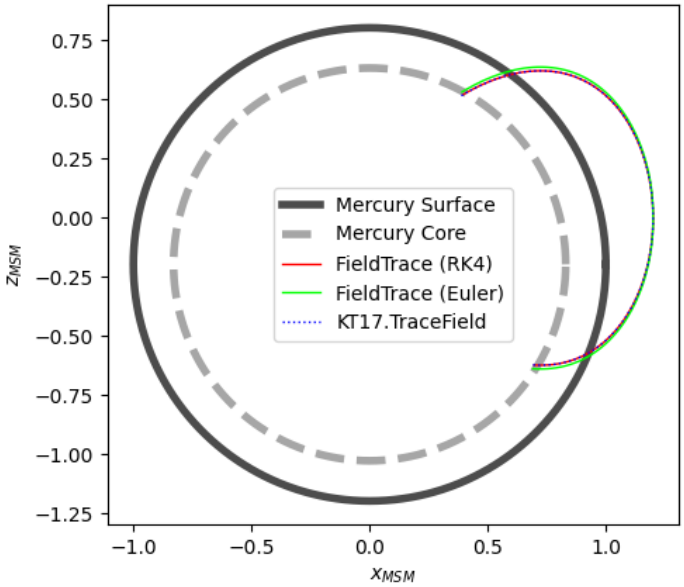


Figure 7.1: Example trace

7.4 DateTimeTools: Tools for dealing with dates and times

A package containing some simple tools to manage dates and times.

7.4.1 Installation

Install using pip3:

```
pip3 install DateTimeTools --user
```

NOTE: This module uses a C++ backend, which is compiled with g++ under Linux (libdatetime.so) and Windows 10 (libdatetime.dll). This code has mostly been tested in Linux (Mint 20ish, CentOS 7) with a very brief test in Windows 10. The precompiled libraries may fail to load under other versions of both operating systems (definitely on Mac, or 32-bit OSes) - if so, then the module will attempt to recompile itself on the host system using g++. If recompilation fails, please check that you have g++ installed - under Linux install GCC, under Windows install Mingw GCC (I used TDM-GCC, be sure to select g++).

7.4.2 Usage

Converting between different date/time formats

Usually this package deals with integer dates in the format yyyymmdd and floating point times in hours since the start of the day.

We can convert to a few different time formats:

```
import DateTimeTools as TT

Date = 20140102
ut = 15.0

#to unix time (seconds since 00:00 1970-01-01)
unixt = TT.UnixTime(Date,ut)
#and back
Date,ut = TT.UnixTimetoDate(unixt)

#to continuous time (hours since 00:00 1950-01-01)
```

```
utc = TT.ContUT(Date,ut)
#and back again
Date,ut = TT.contUTtoDate(utc)

#Julian day
jd = TT.JulDay(Date,ut)
#and back
Date,ut = TT.JulDaytoDate(jd)

#CDF Epoch (milliseconds since 00:00 0000-01-01)
cdfe = TT.CDFEpoch(Date,ut)
#and back
Date,ut = TT.CDFEpochtoDate(cdfe)

#get the python datetime
dt = TT.Datetime(Date,ut)
#or the reverse conversion
Date,ut = TT.DatetimetoDate(dt)

#convert hours since the start of the day to hours,minutes,seconds,milliseconds
hh,mm,ss,ms = TT.DectoHHMM(ut)
#and back
ut = TT.HHMMtoDec(hh,mm,ss,ms)

#Split dates into separate integers
yr,mn,dy = TT.DateSplit(Date)
#or the reverse
Date = TT.DateJoin(yr,mn,dy)
```

Formatted plot tick marks

The DTPlotLabel function can be used to change the plot labels on the x-axis of a matplotlib.pyplot plot such that they resemble human-readable times and dates.

For example:

```
import matplotlib.pyplot as plt

#some plot of a time series
#t is time either in unix time, ContUT, seconds from the start of the day
#or hours from the start of the day
plt.plot(t,x)
ax = plt.gca()

#if we are plotting with t = TT.ContUT(Date,ut)
#the function will be able to work out the date
#The TimeFMT keyword isn't needed here, by default = 'utc'
TT.DTPlotLabel(ax)

#similar to above - we can us unix time
#so t = TT.UnixTime(Date,ut)
#We must let the function know though
TT.DTPlotLabel(ax,TimeFMT='unix')

#With seconds from the beginning of the day, we need to
#tell the function what Date starts at t == 0.0
#NOTE t can go beyond the range 0 < t < 24,
#the labels should include relevant dates
#Also, without the date keyword, just HH:MM(:SS) is shown
TT.DTPlotLabel(ax,TimeFMT='seconds',Date=20150101)

#Plotting with hours since the start of the day is similar
TT.DTPlotLabel(ax,TimeFMT='hours',Date=20190908)
```

Calculating time differences

```
#calculate the difference between two dates in days
ndays = TT.DateDifference(Date0,Date1)

#Similar to above, but include start and end times (still returns days)
ndays = TT.TimeDifference(Date0,ut0,Date1,ut1)

#We can find the middle time between two date/times
mDate,mut = TT.MidTime(Date0,ut0,Date1,ut1)
```

Filtering time series data

Given an evenly sampled time series, the lsfilter function can perform low-pass and high-pass filtering.

```
#t is the evenly sampled time axis
#x is the time series data

#we need to know the sampling interval in seconds
inter = t[1] - t[0]

#we can do a low-pass filter, we need to set 'high = inter'
#and 'low = lsec' which is the cutoff period in seconds
xlow = TT.lsfilter(x,inter,lowsec,inter)

#alternatively a high-pass filter can be used by setting
#'high = hsec' (the cutoff period in seconds) and 'low = inter'
xhigh = TT.lsfilter(x,hsec,inter,inter)
```

Miscellaneous functions

```
#calculate day number and year
year,dayno = TT.DayNo(Date)
#or return to original date format
Date = TT.DayNotoDate(year,dayno)

#Check if year(s) are leap year(s)
ly = TT.LeapYear(year)

#Add one day to a date
NextDate = TT.PlusDay(Date)
#or go back a day
PrevDate = TT.MinusDay(Date)

#Calculate the nearest index in a time/date array
#to a test time/date
ind = TT.NearestTimeIndex(DateArray,utArray,testDate,testut)

#check which indices of a time array are within two time limits
inds = TT.WithinTimeRange(t,t0,t1)
#or including dates
inds = TT.WithinTimeRange((d,t),(d0,t0),(d1,t1))
%alternatively, return a boolean array where each True element is within the range
b = TT.WithinTimeRange((d,t),(d0,t0),(d1,t1),BoolOut=True)
```

7.5 datetime: C++ library dealing for dates and times

A C++ library containing some time-related tools.

7.5.1 Installation

This library requires GNU-make and g++ to be built in Linux and Mac. In Windows, I use TDM-GCC to provide the C++ compiler.

Clone the repo:

```
git clone https://github.com/mattkjames7/datetime.git
cd datetime
```

For Linux or Mac:

```
#build the library
make

#optionally install globally
sudo make install
```

For Windows:

7.5.2 Linking

To link to this library in C or C++, you should include the header for the library:

```
#include <datetime.h>
```

then link to the library, e.g.:

```
#when installed globally
g++ $(CFLAGS) main.cc -o main -ldatetime

#otherwise
g++ $(CFLAGS) -I/path/to/header/ main.cc -o main -L/path/to/lib -ldatetime
```

7.5.3 Testing

To check that all of the functions are working as expected, run the following tests in Linux/Mac:

```
make test
```

or in Windows:

If the library has been installed globally, then the following test will check that linking can be done to the globally installed lib/header:

```
make testinstall
```

7.5.4 Summary of Functions

Name	Description
ContUT()	Converts Date and UT to a continuous value of hours since 19500101 00:00.
ContUTtoDate()	Converts output of ContUT() back to date and time.
DateDifference()	Find the number of days between two dates.
DateJoin()	Join the individual elements of a date (year, month and day) to a single integer w
DateSplit()	Split the date integer into year, month, and day.
DayNo()	Converts a date of the format _yyyymmdd to year and day number.
DayNotoDate()	Converts year and day number to a date with the format _yyyymmdd.
DectoHHMM()	Converts the time in decimal hours to hours, minutes, seconds, and milliseconds.
HHMMtoDec()	Converts hours, minutes, seconds, and milliseconds to decimal hours.
JulDay()	Converts a date and time to Julian day.
JulDaytoDate()	Converts Julian day to date and time.
LeapYear()	Determines whether a year is a leap year or not.
MidTime()	Works out the time and date exactly in the middle of two dates/times.
MinusDay()	Subtracts one day from a date.
NearestTimeIndex()	Finds the index of a time array closest to a given date/time.
PlusDay()	Adds a day to a date.
TimeDifference()	Calculates the time difference (in days) between two dates/times.
UnixTime()	Calculate the Unix time given a date and time.
UnixTimetoDate()	Convert Unix time back to date and UT.
WithinTimeRange()	Find the indices of a time array that lie within two dates/times.

7.6 PyFileIO: Tools for reading and writing files

Some very basic routines for file IO in Python

7.6.1 Installation

Install via pip3:

```
pip3 install PyFileIO --user
```

or from this repo:

```
git clone https://github.com/mattkjames7/PyFileIO
cd PyFileIO

#either this
python3 setup.py install --user

#or this
python3 setup.py bdist_wheel
pip3 install dist/PyFileIO-X.X.X-py3-none-any.whl
```

where X.X.X is the version created.

7.6.2 Usage

This module contains a few different methods of loading/saving data.

Loading/Saving Objects

This effectively uses pickle to load and save physical objects, e.g.:

```
import PyFileIO as pf

#save an object
pf.SaveObject(obj,'/path/to/some/file.bin')

#load an object
obj = pf.LoadObject('/path/to/some/file.bin')
```

Loading/Saving ASCII Data

Text files may be created and read directly:

```
#saving text
text = 'some text, can be an array\n or just a single string'
pf.WriteASCIIFile('filename.txt',text)

#reading text
text = pf.ReadASCIIFile('filename.txt')
```

We can also use ASCII files to load csv files and save data stored in a simple numpy.recarray:

```
#read a csv file, which contains a header - dtype will be worked out automatically
data = pf.ReadASCIIData('somedata.csv')

#we can also save data
pf.WriteASCIIData('newfile.dat',data)
```

NOTE: this will only work with simple dtypes

Loading/Saving Binary Data

Pure binary data may be written to files using the following functions:

```
#open a file
f = open('filename.bin','wb')

#save some stuff
ScalarToFile(x,'int64',f)       #save a single scalar integer
ArrayToFile(y,'float32',f)      #save a floating point array
ListArrayToFile(z,'int32',f)    #save a list of integer arrays
StringToFile(s,f)               #save a string to file

#close the file
f.close()
```

We can also read the data back (remembering to use the correct dtypes!):

```
#open a file
f = open('filename.bin','rb')

#read the stored data
x = ScalarFromFile('int64',f)       #read a single scalar integer
y = ArrayFromFile('float32',f)      #read a floating point array
z = ListArrayFromFile('int32',f)    #read a list of integer arrays
s = StringFromFile(f)               #read a string from file

#close the file
f.close()
```

7.7 RecarrayTools: Tools for manipulating numpy.recarrays

Some simple tools for managing numpy.recarray objects

7.7.1 Installation

Install via pip:

```
pip3 install --user RecarrayTools
```

Or this repo:

```
#clone the repo
git clone https://github.com/mattkjames7/RecarrayTools
cd RecarrayTools

#either use a wheel
python3 setup.py bdist_wheel
pip3 install --user dist/RecarrayTools-0.0.3-py3-none-any.whl

#or just install directly
python3 setup.py install
```

7.7.2 Usage

This module contains a small number of routines...

SaveRecarray()

This will save a record array to a binary file - note that the dtype of the record array shouldn't be too exotic (object arrays would not work - use pickle for those).

```
import numpy as np
import RecarrayTools as RT

#create some recarray
dtype = [('a','int32'),('b','float64',(6,))]
arr = np.recarray(10,dtype=dtype)

#fill it
arr.a = blah #shape (10,)
arr.b = stuff #shape (10,6)

#save it
RT.SaveRecarray(arr,'path/to/file.name',Progress=True)
```

The file format used here is simple:
The first 4 bytes correspond to a 32-bit integer containing the size of the recarray (i.e. arr.size).
Then each field arr.dtype.names is stored contiguously as whatever dtype it was assigned with, one field at a time.
The file created in the above example would be formatted in the following way:
Bytes 0-3: 32-bit integer - total length of the recarray
Bytes 4-43: Array of 32-bit integers, length 10 (arr.a)
Bytes 44-523: Array of 64-bit floating points, shape (10,6), length 60
EOF

ReadRecarray()

This will read in the files created by SaveRecarray(), e.g.

```
dtype = [('a','int32'),('b','float64',(6,))]
fname = 'path/to/file.name'
arr = RT.ReadRecarray(fname,dtype)
```

ReduceRecarray()

This reduces the number of fields in a recarray object, e.g.:

```
#initial object with fields 'a', 'b', 'c' and 'd'
dtype = [('a','int32'),('b','float64',(6,)),('c','int64'),('d','float64')]
obj0 = np.recarray(10,dtype=dtype)

#new object with just fields 'a' and 'c'
obj1 = RT.ReduceRecarray(obj0,['a','c'])
```

JoinRecarray()

Append two recarrays with identical dtypes:

```
C = RT.JoinRecarray(A,B)
```

AppendFields()

Append some extra fields to a recarray:

```
#some initial recarray
A = np.recarray(n,dtype=dtype)

#new fields for the array
x = np.arange(n)
y = x**2

#add them
B = RT.AppendFields(A,[('x','float32'),('y','float32')],(x,y))
#B now has fields B.x and B.y
```

InterpRecarrayFields()

Interpolate fields within a recarray:

```
#a would be the initial recarray, b would be the new recarray
#RefField = name of field to interpolate over
#InterpFields = list of names of fields to interpolate
b = RT.InterpRecarrayFields(a,b,RefField='x',InterpFields=['a','b','c','d','x'])
```

7.8 PBSJobExamples: Examples for submitting jobs to ALICE

TL;DR: Copy one of these folders, $cd into it, add your python code to "runcode.py", edit myjob.sub to have the correct vram etc., then run $ ./submitjob.sh

7.8.1 Templates

This folder contains three templates: "singlejob", "arrayjob" and "paralleljob". Each contains four files which can be tweaked as necessary and one output folder ("out/") which stdout and stderr are written to while the job is running.

singlejob

This template can be used to submit a single job.

arrayjob

This tamplate can be used to submit an array of jobs, where, for example, the same bit of code may be run in each instance, but on a different set of parameters (e.g. date).

The relevant part of the job submission code:

```
#PBS -t 1-1000
```

where 1-1000 indicates a range of job indices from 1 to 1000. This could also be an explicit list, e.g. 2,5,7,99.

paralleljob

This is an example of a parallelised job. This is also an array job, but it is also applicable to single jobs. This will run code which, in each instance, will use multiple cores (e.g. using openMP) and/or nodes (e.g. using openMPI).

The relevant part of the job submission script:

```
#PBS -l nodes=1:ppn=8
```

where nodes=1 denotes the number of nodes over which this code can be distributed upon, and ppn=8 states how many processors to assign per node.

7.8.2 Job Files

It is important that "submitjob.sh" and "startscript.sh" are marked as executable, e.g.

```
chmod +x submitjob.sh
```

submitjob.sh

This script will submit the job to the cluster by running the command: $ ./submitjob.sh

While it isn't necessary - it pretty much just calls the qsub command, it saves some typing and it passes the current working directory to the job script so that the correct output folder is used.

myjob.sub

This contains all of the job configuration options, e.g.

```
#PBS -v WD
```

This passes environment variables from the current session (where the job is submitted) to the running code. In this case WD is the working directory provided in "submitjob.sh".

```
#PBS -o out/output.txt
```

This is the name of the output file where stdout will be saved.

```
#PBS -e out/error.txt
```

This is the output error file where stderr will be saved.

```
#PBS -N ParallelArrayJob
```

This is the name of the job.

```
#PBS -l walltime=0:15:00
```

This is the total amount of time for the job to run in hh:mm:ss. For longer jobs, add days before hours, e.g. dd:hh:mm:ss.

```
#PBS -l vmem=20gb
```

This is the total amount of virtual memory to assign to the job. Ideally, this should not be much more than what it actually requires (more jobs can run at a time in that case).

```
#PBS -m bea
```

This tells the cluster to send an email when each job begins b, ends e or is aborted a. Be warned - this will send those emails for each element of an array job!

```
#PBS -l nodes=1:ppn=8
```

This is for jobs which will be able to use more than one single thread. nodes is the number of nodes requested for each instance of the job. ppn is the number of processors to assign for each node.

```
#PBS -t 1-50
```

Array job range.

After the #PBS options are defined, the rest of this file can be treated as a bash script which will be executed when the job starts. In this case, each job will call $WD/startscript.sh - this isn't necessary, the commands from within "startscript.sh" can be placed directly within this job submission file if desired.

startscript.sh

This file contains the commands to be called when each job runs. It can be placed directly in "myjob.sub", but a separate script is used here. This file is where python or idl may be called, for example.

runcode.py

This file contains the python code to run in the job. It assumes that the job to be submitted will be running python and can be replaced with scripts for other languages as needed.

For array jobs, it is important to access the PBS_ARRAYID environment variable using the os.getenv() function.

7.9 PlanetSpice: SPICE related code

This module is used to obtain information such as Mercury's position around the Sun, Carrington longitude, etc.

7.9.1 Usage

Firstly, a few environment variables need setting:

```
export SPICE_KERNEL_PATH=/path/to/spice/kernels
export SPICE_OUTPUT_PATH=/path/to/output/stuff
```

Also, some dependencies need installing:

```
pip3 install spiceypy RecarrayTools PyFileIO numpy scipy DateTimeTools --user
```

Then we can import the module in Python 3:

```
import PlanetSpice as ps
```

where ps currently contains the following submodules:

- Sun
- Mercury
- Venus
- Earth
- Mars

7.10 ColorString: Change colour of strings in the terminal

7.11 cppembedbinary: Examples for embedding data into C++ code

C++ code to demonstrate how binary data can be embedded into a C++ executable or library.

7.11.1 Building

Clone the repo:

```
git clone https://github.com/mattkjames7/cppembedbinary.git
cd cppembedbinary
```

Running this code requires the g++ and make commands. Under Windows and Linux, the ld command is used for converting the binary into object code, and in MacOS, the xxd command is used instead.
Build the code (this will also run some code):

```
make

# OR if using mingw
mingw32-make
```

In Windows, g++ may be provided by either TDM-GCC or Mingw-w64, and make can be provided by either GNU Win 32 or as mingw32-make by Mingw-w64. You will need to add the paths to the binaries provided by these packages to the %PATH% environment variable.

7.11.2 How it should work

Firstly, the code in readbin.cc will write to a simple binary file called data.bin. The first four bytes of this file will contain a 32-bit integer denoting the length of an array stored immediatel after. In this case, it will be 6 (elements). The array stored directly afterwards is a 6-element array of 32-bit integers:

```
int data[] = {1, 4, 9, 16, 25, 36};
```

Next, data.bin is converted to object code in one of two ways:

- Method 1 uses ld in Linux or Windows to convert it to object code data.o:

```
ld -r -b binary data.bin -o data.o
```

- Method 2 uses xxd in MacOS (this will also work in Linux and may be possible in Windows too) to create data.o. Firstly, it is converted to C code:

```
xxd -i data.bin > data.cc
```

Then, data.cc is compiled to create data.o with similar-looking symbols to Method 1:

```
g++ -c data.cc -o data.o
```

Finally, the resulting binary blob (data.o) can be compiled into code which will try to read it:

```
g++ readbin.cc data.o -o readbin
```

This code requires the definition of the start of the data array within the code:

```
/* for method 1 */
extern unsigned char *_binary_data_bin_start;

/* or method 2 */
extern unsigned char *data_bin;
```

In the example code provided, the pointer unsigned char data$_s tart is assigned to point at which ever of the above u$

For the ld method of embedding the binary data, this site was particularly helpful: http://gareus.org/wiki/embedding_resources_in_executables

Annoyingly, ld in MacOS doesn't allow that, so I found the xxd method from here: https://stackoverflow.com/a/21605198

7.12 libspline: C++ library for splines

Simple spline library in C++

7.12.1 Install

In Linux and Mac, run

```
make

sudo make install
```

Under Windows, run the batch file:

```
.\compile.bat
```

7.12.2 Usage

This package includes a header which is compatible with both C and C++ (spline.c). Below are two very simple examples of how to use this code.

C++

This is a C++ example:

```
/* contents of cppexample.cc */
#include <stdio.h>
#include <spline.h>

int main() {

        /* create arrays of x and y values*/
        double x[] = {-5.0,-4.0,-3.0,-2.0,-1.0,1.0,2.0,3.0,4.0,5.0};
        double y[10];
        int n = 10;
        int i;
```

```
        for (i=0;i<n;i++) {
                y[i] = pow(x[i],3.0);
        }

        /* print the arrays */
        printf("x = [");
        for (i=0;i<n;i++) {
                printf(" %4.1f",x[i]);
                if (i != n-1) {
                        printf(",");
                }
        }
        printf("]\n");

        printf("y = [");
        for (i=0;i<n;i++) {
                printf(" %4.1f",y[i]);
                if (i != n-1) {
                        printf(",");
                }
        }
        printf("]\n");

        /* load the spline object */
        Spline s(n,x,y);

        /* create test position and interpolate */
        double xt, yt;
        xt = 0.0;
        s.Interpolate(1,&xt,&yt);
        printf("y = %3.1f at x = %3.1f\n",yt,xt);


}
```

which can be compiled then run using

```
g++ cppexample.cc -o cppexample -lspline
./compile
```

C

This is a C example, which would work in C++ also. The spline() wrapper function can also be linked to other languages.

```
/* contents of cexample.c */
#include <stdio.h>
#include <spline.h>

int main() {

        /* create arrays of x and y values*/
        double x[] = {-5.0,-4.0,-3.0,-2.0,-1.0,1.0,2.0,3.0,4.0,5.0};
        double y[10];
        int n = 10;
        int i;
        for (i=0;i<n;i++) {
                y[i] = pow(x[i],3.0);
        }

        /* print the arrays */
        printf("x = [");
```

```
        for (i=0;i<n;i++) {
                printf(" %4.1f",x[i]);
                if (i != n-1) {
                        printf(",");
                }\section{libspline}

Simple spline library in C++

\subsection{Install}

In Linux and Mac, run

\begin{minted}{bash}
make

sudo make install

   Under Windows, run the batch file:

.\compile.bat
```

7.12.3 Usage

This package includes a header which is compatible with both C and C++ (spline.c). Below are two very simple examples of how to use this code.

C++

This is a C++ example:

```
/* contents of cppexample.cc */
#include <stdio.h>
#include <spline.h>

int main() {

        /* create arrays of x and y values*/
        double x[] = {-5.0,-4.0,-3.0,-2.0,-1.0,1.0,2.0,3.0,4.0,5.0};
        double y[10];
        int n = 10;
        int i;
        for (i=0;i<n;i++) {
                y[i] = pow(x[i],3.0);
        }

        /* print the arrays */
        printf("x = [");
        for (i=0;i<n;i++) {
                printf(" %4.1f",x[i]);
                if (i != n-1) {
                        printf(",");
                }
        }
        printf("]\n");

        printf("y = [");
        for (i=0;i<n;i++) {
                printf(" %4.1f",y[i]);
                if (i != n-1) {
                        printf(",");
                }
        }
```

```
        printf("]\n");

        /* load the spline object */
        Spline s(n,x,y);

        /* create test position and interpolate */
        double xt, yt;
        xt = 0.0;
        s.Interpolate(1,&xt,&yt);
        printf("y = %3.1f at x = %3.1f\n",yt,xt);


}
```

which can be compiled then run using

```
g++ cppexample.cc -o cppexample -lspline
./compile
```

C

This is a C example, which would work in C++ also. The spline() wrapper function can also be linked to other languages.

```
/* contents of cexample.c */
#include <stdio.h>
#include <spline.h>

int main() {

        /* create arrays of x and y values*/
        double x[] = {-5.0,-4.0,-3.0,-2.0,-1.0,1.0,2.0,3.0,4.0,5.0};
        double y[10];
        int n = 10;
        int i;
        for (i=0;i<n;i++) {
                y[i] = pow(x[i],3.0);
        }

        /* print the arrays */
        printf("x = [");
        for (i=0;i<n;i++) {
                printf(" %4.1f",x[i]);
                if (i != n-1) {
                        printf(",");
                }
        }
        printf("]\n");

        printf("y = [");
        for (i=0;i<n;i++) {
                printf(" %4.1f",y[i]);
                if (i != n-1) {
                        printf(",");
                }
        }
        printf("]\n");


        /* create test position and interpolate */
        double xt, yt;
        xt = 0.0;
```

```
        spline(n,x,y,1,&xt,&yt);
        printf("y = %3.1f at x = %3.1f\n",yt,xt);


}
```

To compile and run:

```
gcc cexample.c -o cexample -lm -lspline
./cexample
```

```
   printf("]");
   printf("y = ["); for (i=0;i<n;i++)  printf(" if (i != n-1)  printf(",");   printf("]");
   /* create test position and interpolate */ double xt, yt; xt = 0.0; spline(n,x,y,1,xt,yt);
printf("y =
```

```
gcc cexample.c -o cexample -lm -lspline
./cexample
```

To compile and run:

```
gcc cexample.c -o cexample -lm -lspline
./cexample
```

7.13 linterp: C++ interpolation code